Which sensor or interface suits for which application?

Jürgen Bretschneider, 2015
Allied Vision Profile

// **Foundation:** 1989, **Headquarters:** Stadtroda (Germany)

// **Employees:** > 300 (2015)

// **Know how:**
- Development and production of high-quality digital cameras for industrial and scientific imaging

// **Research & Development**
- Hardware- and software development of digital cameras for the visible and the infrared spectrum
- Standard cameras and also camera solutions for OEM customers

// **Production**
- Company-owned production sites (cleanroom) in Stadtroda and Osnabrück (Germany), Burnaby BC (Canada)

// **Service**
- Consulting teams for distribution and support, worldwide, 24/5

// **Quality standards**
- Compliance with **ISO-9001** and **ISO 13485**
Optical sensors & electromagnetical spectrum

Parts of the electromagnetic spectrum
Silicon quantum detectors: CCD & CMOS

CCD (analog sensor)

A/D conversion outside the sensor

CMOS (active pixel sensor)

A/D conversion on the sensor
## Sensors for the visible spectrum: CCD- and CMOS sensors

### Advantages of CCD:
- High image quality:
- Low spatial noise (FPN)
- Typically low dark current
- High fill factor (relation of the photo sensitive area to the whole pixel area) generally by larger pixels
- Perfect global shutter
  - Increased sensitivity
  - Good signal quality at low light
- Modern CCDs with multi tap technologies
  - \( n \) times readout speed compared to single tap sensors

### Advantages of CMOS:
- High frame rates, even at high resolution
- Faster and more flexible readout (e.g. several AOIs)
- High dynamic range
  - HDR mode → Acquisition of contrast-rich and extremely bright objects
- No blooming or smear contrary to CCD
- Integrated control circuit on the sensor chip
- More cost-effective and less power consumption than comparable CCD sensors
Sensors for the visible spectrum: CCD- and CMOS sensors

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Recent CMOS sensors deliver:
- Improved **global shutter**
- **Low dark** and **spatial noise** as well
- Good to excellent image quality in **low light condition**
- Higher **quantum efficiency** too

Together with the existing advantages in **speed** and **cost** which makes CMOS sensors suitable for a lot of vision applications!
Where can CCD can survive - Applications for CCD cameras

Acquisition with minimal noise
Low light intensities
- Microscopy
  // Fluorescence microscopy
  // High resolution microscopy

- Astronomy (long exposure time)
- High resolution and high quality images
- Bioluminescence / Chemoluminescence
- Science

Full Frame CCD Imagers, e.g. KAF-6303E

Bigeye G-629B Cool
blooming and smear – test images of CCD and CMOS sensors

CCD (ICX 285)  CMOS (CMV2000)  CMOS (MT9P006)

blooming and smear:
- Charge overflow between neighboring pixels
- Unwanted charge in the vertical shift register

Black sun effect:
Overloaded pixel cell with charges
-> reset level of the CDS is already in saturation
Current sensors (V3) show reduced black sun effect

Pixels not affected by blooming and smear
High dynamic range mode (CMOS)

**Dedicated exposure control:**
- The pixels’ saturation level is controlled by “knee points”
- The response curve between the knee points is linearly controlled
- The exposure time is automatically controlled

→ For applications with high light intensities
    (e.g. laser welding, high-contrast objects, night shots with spot lights)
Penetration Depth in Silicon vs. Wavelength

Source: Arnaud Darmont, Aphesa (www.aphesa.com), White paper, April 2009
CMOSIS CMV2000 & CMV4000 NIR sensors (up to 1000 nm)

CMOS variants with increased NIR sensitivity

- Sensor with 12 µm epitaxial silicon layer
  → increased absorption of photons in the red and NIR spectrum
  → Increase of the quantum efficiency (QE) for wavelengths > 600 nm
- Doubling of the QE @ 900 nm from 8 % to 16 %

- Consider MTF!
  Crosstalk of electrons generated deep in the epi layer, caused by the low electrical field strengths
Sony Exmor and Exmor R CMOS Sensors

“Pregius”
- Global shutter pixel technology
- Front-illuminated pixel technology *Exmor*

“STARVIS”
- Visibility under starlight
- Back-illuminated pixel technology *Exmor R*

Source: http://www.sony.net/Products/SC-HP/sensor/technology/starvis.html
Sony Exmor global shutter CMOS sensors
e.g. IMX 174 (1/1.2“, 2.35 MP, 5.86 µm pixel size)

**IMX 174 - Sony's 1st global shutter CMOS**

- **High sensitivity:** >75% Qe @530 nm
- **High DNR:** (> 70 db) based on Sony's CCD pixel technology, saturation capacity: ~ 32.000 e-
- **fully shielded memory** - low dark current noise and nearly no unwanted parasitic light
- **High frame rate** – column parallel A/D conversion
  (IMX174: 164 fps@10 bit, 128 fps@12 bit)
- **Analog CDS + digital CDS = dual noise reduction**
  Noiseless high-speed data transfer via LVDS

→ higher possible shutter speed, less image blur of fast moving objects and high frame rates
→ MV and ITS applications
Sony Exmor pixel architecture evolution

1st gen Pregius
IMX 174
IMX 249
5.86 µm
dn < 7 e-
FW 32 ke-

2nd gen Pregius
IMX 250
IMX 252
IMX 253
IMX 264
IMX 265
3.45 µm
dn < 3 e-
FW 10 ke-

Python - global shutter CMOS Sensors

New global shutter CMOS sensor family with resolutions of 0.3 MP (VGA) to 5 MP with 4.8 µm x 4.8 µm Pixel size and 10 MP to up to 25 MP with 4.5 µm x 4.5 µm Pixel size

Suitable for general purpose industrial imaging applications in machine vision as well as for security and surveillance applications including intelligent transportation systems (ITS)

**Features:**

- in-pixel CDS (ipCDS) technology enabling global shutter imaging with < 10e- read noise, FW ~10ke-
- High frame rates
  - 550 frames per second @ 0.3 MP (1/4”)
  - 400 frames per second @ 0.5 MP (1/3.6”)
  - 170 frames per second @ 1.3 MP (1/2”)
- High NIR sensitivity
- High dynamic range
- Multiple Region Of Interest
Applications for CMOS cameras - high speed

Laser triangulation for 3D measurements

// Camera Bonito CL-400B

- max. frame rate : 386 fps @ 2320 x 1726 pixels

// max. scan frequency: **5200 profiles per second** @ 2320 x 128 pixels
Applications for CMOS cameras - high speed

„Fast tracking“ - motion analysis with markers @ 200 – 400 frames per second

- Applications:
  - Motion analysis for sports and wildlife
  - Golf swing analysis with camera Mako G-030
  - Generation of slow motion pictures
What is Short-wave Infrared?

Visible
400-750nm

NIR
750-1000nm

SWIR
900-2500nm

CCD/CMOS
NIR Enhanced CCD/CMOS
Standard InGaAs
Extended InGaAs
InGaAs sensor - seeing the invisible

- Spectral sensitivity (900 – 1700 nm)
- High dynamic range (>73 dB)
- High spatial resolution (15 µm pixel)
- Frame rates up to 301 fps
What differs a SWIR camera from a classic Machine Vision camera?

1. **InGaAs Detector**
   - Sensitivity between 900 and 1,700 nm
   - High complexity level in the production process
   - Defect pixels on every sensor
   - Non-uniform pixel behavior
   - Higher dark current than CCD, CMOS

2. **Cooling Capability**
   - Due to the higher Dark Current of InGaAs sensors, cooling is necessary

3. **Advanced image correction features**
   - Non-uniformity correction (NUC)
   - Defect Pixel Correction
   - Background Correction
Applications for SWIR cameras

Checking the contacts of a TFT or underlying structures in a wafer
(> 1100 nm: Silicon appears transparent)

Electroluminescence inspection of solar cells
(Silicon emits light @ 1150 nm)

Inspection of hypodermic needles inside sleeve
(> 1100 nm: some plastics appear transparent)
Applications for SWIR cameras

Control of filling level

Early detection of fruit bruises

> 1350 nm water looks dark
Applications for SWIR cameras - Hot-End Glass Inspection

Hot-End Glass Inspection

// Monitoring of glass temperature uniformities and cooling rate from 800°C to 250°C
// Interior and exterior walls inspection
→ Improvement of yield and quality

Reference temps:
White hot steel ~1200 °C
Melting point of aluminum 660 °C
Water boils at 100 °C
Uncooled camera at 38 °C
Human body at 37 °C, radiates at ~ 10 μm
Water freezes at 0 °C

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Applications for SWIR cameras - Hyperspectral Imaging

Hyperspectral Imaging (HIS) combines digital imaging with spectroscopy to obtain detailed information across multiple ranges of the electromagnetic spectrum.

**Applications:**

- Recycling & Plastic Sorting
- Geology & Mineral Inspection
- Pharmaceutical Quality Control
- Food & Agriculture
- Medical e.g. Disease Diagnosis
Camera interface comparism

**USB3 Vision**: no frame grabber required, 10 x faster than USB2.0, limited cable length, cover speed of current CCD/ CMOS sensors and overcome speed limitation of Firewire

**GigE Vision**: High Consumer acceptance for standard vision systems, which require longer cable lengths up to 100m, cost effective solutions, 1 cable solution with PoE, covers most of the current CCD and CMOS sensor speed requirements

**10 GigE Vision**: based on GigE Vision, 10 times faster, but higher power consumption, need expensive server grade equipment

**Camera Link**: Industrial standard, which covers requirements for higher speed, expensive cables, limited cable length, point to point connection

**Camera Link HS**: speed improvement over Camera Link – up to 2100 MB/s with one cable and 16800 MB/s with 8 cables, expensive, mostly for linescan application

**CoaxPress**: for high speed application, industrial proofed Coax cable, low cable costs, requires a frame grabber
Camera interface speed (1 cable) vs. sensor speed

Recent and future CMOS sensors (Sony, OnSemi, CMOSIS,...) need bandwidth > 100 MB/s!

CMOSIS CMOS @ 12bit

Sony Pregius CMOS @ 10/12 bit
OnSemi Python @ 8/10 bit

- Multi camera application
- Byte depth (Mono 8, YUV422, RGB8)

CCD & CMOS @ 8bit

Image data throughput MB/s

0 200 400 600 800 1000 1200 1400

Firewire 800  GigE  USB 3.0  Camera Link  Coaxpress  10 GigE  Camera Link HS Thunderbolt 1 (SFP+)

Camera interface
## Comparing Digital Interfaces

<table>
<thead>
<tr>
<th></th>
<th>FireWire</th>
<th>GigE</th>
<th>Camera Link</th>
<th>USB 3.0</th>
<th>CoaXPress</th>
<th>HS Link</th>
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<tbody>
<tr>
<td>Bandwidth per link</td>
<td>80 MB/s</td>
<td>100+ MB/s</td>
<td>250-850 MB/s</td>
<td>350+ MB/s</td>
<td>625 MB/s</td>
<td>300 – 2100 MB/s</td>
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<td>(multiple links possible)</td>
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<tr>
<td>Cable length</td>
<td>10 m</td>
<td>100 m</td>
<td>10 m</td>
<td>3–10 m</td>
<td>105 m (CXP1)</td>
<td>15 m (CX4)</td>
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<tr>
<td>Power + data on one</td>
<td>Yes</td>
<td>PoE</td>
<td>PoCL</td>
<td>Yes</td>
<td>Yes</td>
<td>None</td>
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<tr>
<td>cable</td>
<td>45 W</td>
<td>13 - 25 W</td>
<td>4 - 8 W</td>
<td>Yes</td>
<td>13 - 52 W</td>
<td>N/A</td>
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<tr>
<td>Hotplugging</td>
<td>N/A</td>
<td>Medium</td>
<td>Poor</td>
<td>Very good</td>
<td>Poor</td>
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<tr>
<td>System cost</td>
<td>Medium-Low</td>
<td>Low</td>
<td>High</td>
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<td>CPU usage</td>
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<td>Medium</td>
<td>Medium</td>
<td>Low</td>
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<td>Consumer acceptance</td>
<td>Declining</td>
<td>Excellent</td>
<td>Declining</td>
<td>Good</td>
<td>Growing</td>
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<tr>
<td>Multiple cameras</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
<td>Excellent</td>
<td>Fair</td>
<td>Fair</td>
</tr>
</tbody>
</table>

With the broad range of requirements addressed by machine vision systems, there is no single interface that can address them all. Each interface has its own unique strength that makes it more effective and efficient for certain kinds of applications.
Thank You/Q&A

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