Metrology and Sensing

Lecture 3: Sensors
2019-10-29
Herbert Gross
<table>
<thead>
<tr>
<th>No</th>
<th>Dat</th>
<th>Subject</th>
<th>L</th>
<th>Detailed Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.10.</td>
<td>Introduction</td>
<td>HG</td>
<td>Introduction, optical measurements, shape measurements, errors, definition of the meter, sampling theorem</td>
</tr>
<tr>
<td>2</td>
<td>22.10.</td>
<td>Wave optics</td>
<td>IS</td>
<td>Basics, polarization, wave aberrations, PSF, OTF</td>
</tr>
<tr>
<td>3</td>
<td>29.10.</td>
<td>Sensors</td>
<td>HG</td>
<td>Introduction, basic properties, CCDs, filtering, noise</td>
</tr>
<tr>
<td>4</td>
<td>05.11.</td>
<td>Fringe projection</td>
<td>IS</td>
<td>Moire principle, illumination coding, fringe projection, deflectometry</td>
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<td>5</td>
<td>12.11.</td>
<td>Interferometry I</td>
<td>IS</td>
<td>Introduction, interference, types of interferometers, miscellaneous</td>
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<tr>
<td>6</td>
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<td>Interferometry II</td>
<td>IS</td>
<td>Examples, interferogram interpretation, fringe evaluation methods</td>
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<tr>
<td>7</td>
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<td>Wavefront sensors</td>
<td>HG</td>
<td>Hartmann-Shack WFS, Hartmann method, miscellaneous methods</td>
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<tr>
<td>8</td>
<td>03.12.</td>
<td>Geometrical methods</td>
<td>IS</td>
<td>Tactile measurement, photogrammetry, triangulation, time of flight, Scheimpflug setup</td>
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<tr>
<td>9</td>
<td>10.12.</td>
<td>Speckle methods</td>
<td>IS</td>
<td>Spatial / temporal coherence, speckle, properties, speckle metrology</td>
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<td>10</td>
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<td>Holography</td>
<td>IS</td>
<td>Introduction, holographic interferometry, applications, miscellaneous</td>
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<tr>
<td>11</td>
<td>07.01.</td>
<td>Measurement of basic system properties</td>
<td>HG</td>
<td>Basic properties, knife edge, slit scan, MTF measurement</td>
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<tr>
<td>12</td>
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<td>Phase retrieval</td>
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<td>Introduction, algorithms, practical aspects, accuracy</td>
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<td>13</td>
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<td>Metrology of aspheres and freeforms</td>
<td>HG</td>
<td>Aspheres, null lens tests, CGH method, metrology of freeforms</td>
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<tr>
<td>14</td>
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<td>OCT</td>
<td>HG</td>
<td>Principle of OCT, tissue optics, Fourier domain OCT, miscellaneous</td>
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<tr>
<td>15</td>
<td>04.02</td>
<td>Confocal sensors</td>
<td>HG</td>
<td>Principle, resolution and PSF, chromatical confocal method</td>
</tr>
</tbody>
</table>
Content

- Introduction
- Basic properties
- CCD
- Filtering
- Noise
- Signal chain

- Optical signal detection

\[ S(x, y) = [K \cdot B(x, y) \ast T(x, y)] \cdot Comb(x, y) + N_D(x, y) \]

- \( T \) : transfer function
- \( B \) : signal conversion
- \( N \) : noise
Classification of sensors according to physical principle
1. absorption and growing temperature
2. change of conductivity
3. chemical reaction
4. generation of electrical current

Different properties of
1. spectral sensitivity
2. time behavior
3. dependence on temperature
4. sensitivity of signal power
- Recording of a signal

- Dependencies:
  1. space coordinate and angle
  2. time
  3. wavelength
2D sensor: Discrete pixel of finite size

Dead zones between pixels: finite effective area of signal collection

$$\eta = \left( \frac{p}{D_{\text{pixel}}} \right)^2$$
Pixelation and Quantization

- Discrete pixel area of finite size
  1. integration
  2. averaging
  3. dead area
  4. finite spatial resolution

- Nyquist frequency of spatial resolution

\[ v_{Ny} = \frac{1}{2D_{\text{pixel}}} \]
Digitization of the Signal

- Combined effect of spatial discretization and digitization
- Averaging and rounding of signals per pixel
- Rounding corresponds to noise

**Signal S**

*Input signal*

*Input signal after pixel integration*

*Input signal after pixel integration and digitizing*

Yellow: $\delta l < 0$
Blue: $\delta l > 0$
- Acceptance angle of optical sensor
- Sensitivity of the response on the incidence angle
- Empirical description: generalized cos-law $s(\theta) = s_0 \cdot \cos^m \theta$
- Largest sensitivity for normal incidence

![Graph showing sensitivity on direction with different values of m]
Detection of Color

- Wavelength sensitive detection with CCD:
  - array structures with different spectral sensitivity
  - reduced spatial resolution
- Alternatives:
  - depth resolved layers
  - time multiplexing
  - spatial separation by filter
• Spectral properties:
  sensitive in VIS and NIR

• Degrading effects:
  1. diffusion of electrons, blooming
  2. dead zones, reduced efficiency
  3. noise of reading process
  4. dark current
  5. quantum efficiency, 80%
  6. time delay, hysteresis
Spectral Sensitivity of a CCD Sensor

- Typical sensor of a SLR photo camera: Canon 5D
- RGB sensitivity curves at daylight

Ref: D. Gängler
Layout of a modern CCD camera
- The spot position is more accurate, if its size is larger than the pixel width.
- The signal is changed in many pixels, this is more accurate.
- Spot inside one pixel: exact position cannot be distinguished.

Resolution and Spot size

\[
\text{small spot: equal signal } \quad \Delta x = x_2 - x_1 \quad \text{not measurable}
\]

\[
\text{large spot: different signal } \quad \Delta x = x_2 - x_1 \quad \text{is measurable}
\]
- Optical system with fixed camera position
- Change of object distance:
  - s too small: broadening of spot
  - focussed: optimal signal transfer
  - s too large: broadening of spot, saturation for extreme distances
Gain of information as a function of the object distance

Gain of information as a function of the object distance.
Discretization of the Signal

- Quantization of signal in intervals of finite size $\Delta I$
- Typical powers of 2 are used
  8 bit corresponds to 256 value of the signal
- Rounding of real numbers is equivalent to signal noise
- Noise equivalent power
- Representation of discretized black-white image as gray levels

$$M = 2^b = \frac{I_{\text{max}}}{\Delta I}$$

$$\frac{S}{N} = 6 \cdot B [\text{dB}]$$

$$P_{\text{noise,quant}} = k \cdot \frac{\Delta I^2}{12}$$
Characteristic Numbers of Sensors

- System model: sensor signal as function of measuring quantity
  ideal case: linear behavior
  sensitivity: slope

- Characteristic numbers of a sensor:
  1. sensitivity
  2. stability
  3. accuracy
  4. speed of response
  5. hysteresis
  6. life time
  7. cost
  8. size and weight
  9. spatial resolution
  10. linearity
  11. range of acceptance, dynamic range
  12. selectivity
  13. size of dead zones

\[ S = s \cdot a + b \]

\[ s = \left. \frac{dS(a)}{da} \right|_{a=a_o} \]
• Accuracy of a sensor: error of signal for a given input

• to be distinguished:
  1. calibration
  2. hysteresis
  3. reproduction
  4. sample scatter
Hysteresis:
the size of the signal depends on the fact, if the input is increasing / decreasing
- Every sensor has a finite range of operation for the input stimulus
- Limitations:
  - upper limit: saturation
  - lower limit: noise
- Removed input:
  - sensor reacts with a delay
  - switch-on curve with characteristic delay time

- Alternative description:
  - frequency response for periodic activation
  - maximum acceptance frequency
Time Response

- Step response:
  - usually oscillations
  - damping feasible
Photoconductive sensors:
inner and outer photo effect
photon extracts electron out of the binding
photo current measured

Important:
- materials
- gain
- geometry

\[ \Phi_{ph} = \frac{J}{e \cdot \eta(\lambda)} \]
- Solid state array of sensitive pixels
- Types:
  - CCD, CMOS, CID
- Typical size:
  - pixel length 2-20 μm
## Color Sensor

Bayer mask of color sensor

Possible algorithms in signal processing:

<table>
<thead>
<tr>
<th>Non-adaptive</th>
<th>Adaptive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nearest neighbor replication</td>
<td>Edge scaling interpolation</td>
</tr>
<tr>
<td>Bilinear interpolation</td>
<td>Interpolation with color correction</td>
</tr>
<tr>
<td>Cubic convolution</td>
<td>Variable number gradient method</td>
</tr>
<tr>
<td>Smooth hue transition</td>
<td>Pattern recognition</td>
</tr>
<tr>
<td>Smooth logarithmic hue transition</td>
<td>Pattern matching interpolation</td>
</tr>
</tbody>
</table>

Ref: E. Derndinger
## Sensor Formats

**Digital sensor formats**

<table>
<thead>
<tr>
<th>Sensor (mm)</th>
<th>Type</th>
<th>Aspect Ratio</th>
<th>Dia. tube (mm)</th>
<th>Diagonal</th>
<th>Width</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/3.6&quot;</td>
<td>4:3</td>
<td>7.056</td>
<td>5.000</td>
<td>4.000</td>
<td>3.000</td>
</tr>
<tr>
<td></td>
<td>1/3.2&quot;</td>
<td>4:3</td>
<td>7.938</td>
<td>5.680</td>
<td>4.536</td>
<td>3.416</td>
</tr>
<tr>
<td></td>
<td>1/3&quot;</td>
<td>4:3</td>
<td>8.467</td>
<td>6.000</td>
<td>4.800</td>
<td>3.600</td>
</tr>
<tr>
<td></td>
<td>1/2.7&quot;</td>
<td>4:3</td>
<td>9.407</td>
<td>6.721</td>
<td>5.371</td>
<td>4.035</td>
</tr>
<tr>
<td></td>
<td>1/2.5&quot;</td>
<td>4:3</td>
<td>10.160</td>
<td>7.182</td>
<td>5.760</td>
<td>4.290</td>
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<tr>
<td></td>
<td>1/2.3&quot;</td>
<td>4:3</td>
<td>11.044</td>
<td>7.70</td>
<td>6.16</td>
<td>4.62</td>
</tr>
<tr>
<td></td>
<td>1/2&quot;</td>
<td>4:3</td>
<td>12.700</td>
<td>8.000</td>
<td>6.400</td>
<td>4.800</td>
</tr>
<tr>
<td></td>
<td>1/1.8&quot;</td>
<td>4:3</td>
<td>14.111</td>
<td>8.933</td>
<td>7.176</td>
<td>5.319</td>
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<tr>
<td></td>
<td>1/1.7&quot;</td>
<td>4:3</td>
<td>14.941</td>
<td>9.500</td>
<td>7.600</td>
<td>5.700</td>
</tr>
<tr>
<td></td>
<td>2/3&quot;</td>
<td>4:3</td>
<td>16.933</td>
<td>11.000</td>
<td>8.800</td>
<td>6.600</td>
</tr>
<tr>
<td></td>
<td>1&quot;</td>
<td>4:3</td>
<td>25.400</td>
<td>16.000</td>
<td>12.800</td>
<td>9.600</td>
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<tr>
<td></td>
<td>4/3&quot;</td>
<td>4:3</td>
<td>33.867</td>
<td>22.500</td>
<td>18.000</td>
<td>13.500</td>
</tr>
<tr>
<td></td>
<td>Cine 35mm</td>
<td>4:3</td>
<td>31.15</td>
<td>24.9</td>
<td>18.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.8&quot; APS-C</td>
<td>3:2</td>
<td>45.720</td>
<td>28.400</td>
<td>23.700</td>
<td>15.700</td>
</tr>
<tr>
<td></td>
<td>35 mm film</td>
<td>3:2</td>
<td>n/a</td>
<td>43.300</td>
<td>36.000</td>
<td>24.000</td>
</tr>
</tbody>
</table>

Ref: D. Gängler
CCD Sensor

- Architecture:
  3 different types of carrier transport
  1. full frame
  2. interline
  3. frame transfer
CCD-Sensors

- **Typical dimensions**

<table>
<thead>
<tr>
<th>Size [mm]</th>
<th>Diagonal [mm]</th>
<th>Pixel size [μm]</th>
<th>Pixel number</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.8</td>
<td>9.6</td>
<td>16</td>
<td>768</td>
</tr>
<tr>
<td>8.8</td>
<td>6.6</td>
<td>11</td>
<td>768</td>
</tr>
<tr>
<td>6.4</td>
<td>4.8</td>
<td>8</td>
<td>768</td>
</tr>
<tr>
<td>4.8</td>
<td>3.6</td>
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<td>768</td>
</tr>
<tr>
<td>3.2</td>
<td>2.4</td>
<td>4</td>
<td>768</td>
</tr>
</tbody>
</table>

- **Optical effect of arrays:**
  - dead zone and change of acceptance angle

![signal / loss](CCD-CCD-CCD-CCD)

![signal](CCD-CCD-CCD-CCD)

active detector areas
CCD-Sensors

- Spatial transfer function: depends on shape and direction of illumination

- Noise behavior
## Setup of internal elements

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thick</th>
<th>Height</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>MicroLen</td>
<td>0.75</td>
<td>7.61</td>
<td>1.58</td>
</tr>
<tr>
<td>FOC</td>
<td>0.55</td>
<td>6.86</td>
<td>1.51</td>
</tr>
<tr>
<td>Filter</td>
<td>1.0</td>
<td>6.31</td>
<td>1.54</td>
</tr>
<tr>
<td>FOC</td>
<td>0.45</td>
<td>5.31</td>
<td>1.51</td>
</tr>
<tr>
<td>Pass2</td>
<td>0.2</td>
<td>4.86</td>
<td>2</td>
</tr>
<tr>
<td>Pass1</td>
<td>1.16</td>
<td>4.66</td>
<td>1.46</td>
</tr>
<tr>
<td>IMD3</td>
<td>0.88</td>
<td>3.5</td>
<td>1.46</td>
</tr>
<tr>
<td>Metal 3</td>
<td>0.43</td>
<td>3.05 na</td>
<td>1.46</td>
</tr>
<tr>
<td>IMD2</td>
<td>0.82</td>
<td>2.62</td>
<td>1.46</td>
</tr>
<tr>
<td>Metal 2</td>
<td>0.43</td>
<td>2.23 na</td>
<td>1.46</td>
</tr>
<tr>
<td>IMD1</td>
<td>0.82</td>
<td>1.8</td>
<td>1.46</td>
</tr>
<tr>
<td>Metal 1</td>
<td>0.43</td>
<td>1.41 na</td>
<td>1.46</td>
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<tr>
<td>ILD</td>
<td>0.6</td>
<td>0.98</td>
<td>1.46</td>
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<tr>
<td>Poly</td>
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<td>0.58 na</td>
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<tr>
<td>FOX</td>
<td>0.38</td>
<td>0</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Ref: D. Gängler
- Chemical detector
- Photons change silver salt atom
- Size of grains defines spatial resolution
- MTF depends on spectrum
- Typical: 50% contrast at 100 Lp/mm
- Contrast for limiting frequency 1000 Lp/mm
- Photolayer darkening
  Linearity in medium range of brightness
- Description of sensitivity with the optical density $D$
  \[ \gamma = \frac{\Delta D}{\Delta \log(H)} \]
- Solarization at higher density
Detector Sampling

- Discrete pixelized detector: sinc-transfer function
Signal Filtering

- **Low-pass filtering:**
  - suppression of high-frequency signals

- **Numerical realization:**
  - Fourier spectrum limited
  - smooth truncations filters to avoid oscillations

- **Typical effects:**
  - side lobes
  - reduced gradients
  - higher frequencies damped

- **Well known filter solutions:**
  - rectangle
  - Hanning
  - Hamming
  - Blackman
  - Bartlett, Dreieck

![Graph showing signal filtering effects](image)
Signal Filtering

Filter spectrum $W(\nu)$

Filter function $W(x)$ linear

Filter function $\log W(x)$ logarithmic

rectangle

Hanning

Triangle

Hamming

Blackman
### Savitzky-Golay Filter

- Fit of polynomial with order \( k \) and \( N \) points

- Good conservation of gradients

- Features with higher frequency content preserved

<table>
<thead>
<tr>
<th>( N )</th>
<th>( k = 15 )</th>
<th>( k = 35 )</th>
<th>( k = 61 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>![Image for N=41]</td>
<td>![Image for N=41]</td>
<td>![Image for N=41]</td>
</tr>
<tr>
<td>81</td>
<td>![Image for N=81]</td>
<td>![Image for N=81]</td>
<td>![Image for N=81]</td>
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<tr>
<td>151</td>
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<td>![Image for N=151]</td>
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<td>![Image for N=251]</td>
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<td>351</td>
<td>![Image for N=351]</td>
<td>![Image for N=351]</td>
<td>![Image for N=351]</td>
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<tr>
<td>491</td>
<td>![Image for N=491]</td>
<td>![Image for N=491]</td>
<td>![Image for N=491]</td>
</tr>
</tbody>
</table>
Optimization of
1. polynomial order $k$
2. number of points $N$

Savitzky-Golay Filtering

Limit $N_{\text{min}}$

$N = \frac{N_{\text{ges}}}{4}$

$k = N$

$\text{Rms Grenze}$

$N_{\text{min}}$
Noise

Types of noise in photo-electric sensors:

- photons noise
- Flicker noise due to elektrons
- fix-pattern noise
- Reset noise
- Dark current, Schrot, thermal noise
- Excess noise of gain
- Quantization noise

Superposition of noise reasons:

\[
\left( \frac{S}{N} \right)_{\text{many}} = \sqrt{n} \cdot \left( \frac{S}{N} \right)_{\text{single}}
\]
Generation of noise in photo-electric sensors

- Quantum noise
- Photoelectron noise
- Fixed pattern + reset noise
- Thermal dark-current noise
- Transit time noise
- Optional for digitization
- Optional for amplification

Signal

Photo current

Noise
- Thermal white noise

\[ P_R = 4k_B T \]

- Flicker noise

\[ P \propto \frac{1}{f} \]

- Schottky noise of runtime

\[ P = 2e \cdot \Delta f \cdot I_0 \cdot R \]

- Dominating noise depends on frequency

![Diagram showing different types of noise and their frequency characteristics.]
Quantum Noise and Lock-in

- Poisson statistics of photons: quantum noise for small signal strengths

- Width of distribution

\[ \Delta N = \sqrt{N} \]

- Lock-in: improvement of signal to noise ratio by transform into low-noise band
Quantum Noise

Poisson noise and white noise

original signal

10 % Photon noise

10 % white noise
Noise

Characteristic:

Noise grows with
1. time of integration
2. size of detector area
Noise reduction and subtraction of background