Automated Feature Extraction with Machine Learning and Image Processing

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X-ray Imagaing and Data

- Physical principles behind X-ray RAdiography and Computer Tomography
- Metrics of Data
- Noise and Distortions in Measuring Processes; Data Noise
- Finally: Data-driven Feature Extraction in X-ray Images (ML). Models, Algorithms, Issues

Further Readings

1. M. Berger, Q. Yang, and A. Maier, “X-ray Imaging,” in Medical Imaging Systems, Springer, 2018.
2. S. Bosse, Automated Damage and Defect Detection with Low-Cost X-Ray Radiography using Data-driven Predictor Models and Data Augmentation by X-Ray Simulation, The 10-th International Electronic Conference on Sensors and Applications (ECSA), Session Sensors and Artificial Intelligence, MDPI https://doi.org/10.3390/ecsa-10-16126 2023
3. Schiebold, Zerstörungsfreie Werkstoffprüfung – Durchstrahlungsprüfung, 2015

X-ray Radiation

- X-rays belong to the group of electromagnetic rays, hence, they follow the rules of electromagnetic radiation.

[Berger, Yang, Maier, Medical Imaging Systems, 2018]

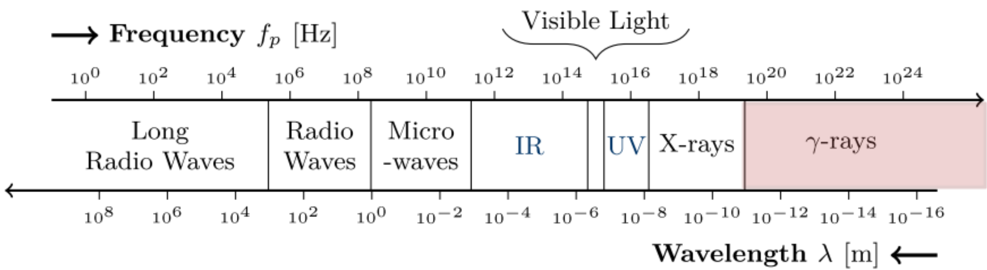


Fig. 1. Wavelengths and frequencies of the different groups of electromagnetic radiation. X-rays lie in the range of 0.01nm up to 10nm.

X-ray Radiation

- In industry, X-rays are often the method of choice, for example to test for very small cracks in metal parts in the field of non-destructive testing.

- The photon energy *E* is proportional to its frequency *f* and inverse proportional to its wavelength λ, that means the higher its frequency, the higher its energy:

$$E_p = \frac{hc_0}{\lambda_p} = f_p h$$

- Typical energies in NDT: 30-120 keV ⇔ 0.04nm - 0.01nm

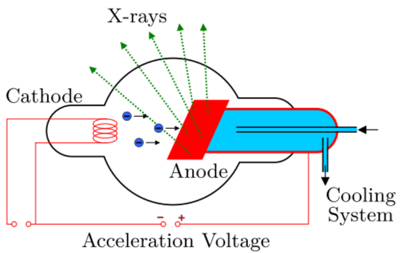
X-ray Generation

- An X-ray tube is commonly used for X-ray generation
- An X-ray tube is an evacuated tube made of glass (rarely metal or ceramics) with a cathode and a solid metal anode in it.
- Thermionic emission occurs by the heated filament at the cathode.
- Heat induced electrons e^- are produced because the thermal energy applied to the filament material is larger than its binding energy.
- Then, the electrons are accelerated by the tube's acceleration voltage between the negative cathode and the positive anode.
- When those fast electrons hit the anode, they are decelerated and deflected by the electric field of the atoms of the anode material.
- Any acceleration of loaded particles results in electromagnetic waves.
- The slowing down, i. e., the negative acceleration, of the electrons in the metal anode, generates X-rays.

X-ray Generation

- The anode is tilted by a certain angle to direct the emerging X-rays in the right direction. The angle determines the Focal Spot Size (FSD), and hence the imaging resolution, discussed later!

[Berger, Yang, Maier, Medical Imaging Systems, 2018]



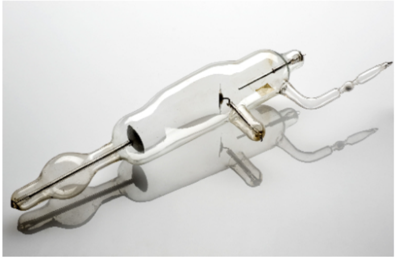


Fig. 2. Vacuum X-ray tube: The image on the left shows a schematic how electrons are accelerated from the cathode to the anode to generate X-ray photons. The image on the right shows a historic vacuum X-ray tube.

X-ray Generation

The production of X-rays is caused by two different processes:

1. Electron Interaction (Discrete)
2. Nucleus interaction (Continuous)

The firs process: The electron interacts with an inner-shell electron of the target, characteristic X-radiation can be produced. This kind of X-rays results from a sufficiently strong interaction that ionizes the target atom by a total removal of the inner-shell electron.

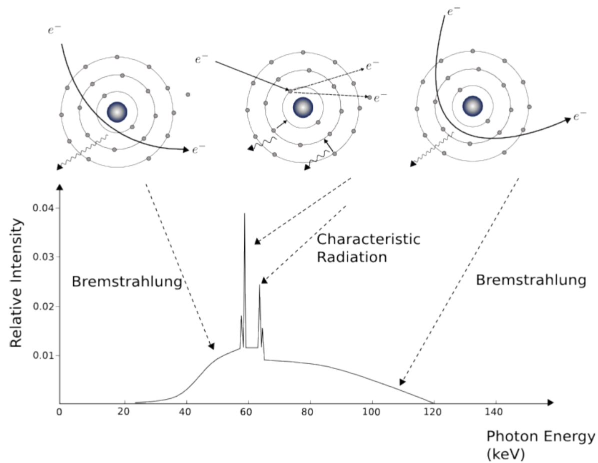
- The transition of an orbital electron from an outer-shell to an inner-shell is accompanied by the emission of an X-ray photon, with an energy equal to the difference in the binding energies of the orbital electrons involved.

X-ray Generation

Another type of interaction in which the electron can lose its kinetic energy delivers the second process of X-ray production:

- Caused by the interaction of the electron with the nucleus of a target atom.
- As the colliding electron passes by the nucleus of an anode atom, it is slowed down and deviated, leaving with reduced kinetic energy in a different direction.
- This loss in kinetic energy reappears as an X-ray photon. This type of X-rays is called **Bremsstrahlung**,
- The amount of kinetic energy that is lost in this way can vary from zero to the total incident energy ⇒ Continuous energy distribution!

X-ray Generation



[Berger, Yang, Maier, Medical Imaging Systems, 2018]

Fig. 3. X-ray spectrum of a tungsten tube. The peaks correspond to the characteristic radiation; the continuous part of the spectrum represents the Bremsstrahlung. **Maximum** ≡ **U_{HV} keV**

X-ray Material Interaction

[Berger, Yang, Maier, Medical Imaging Systems, 2018]

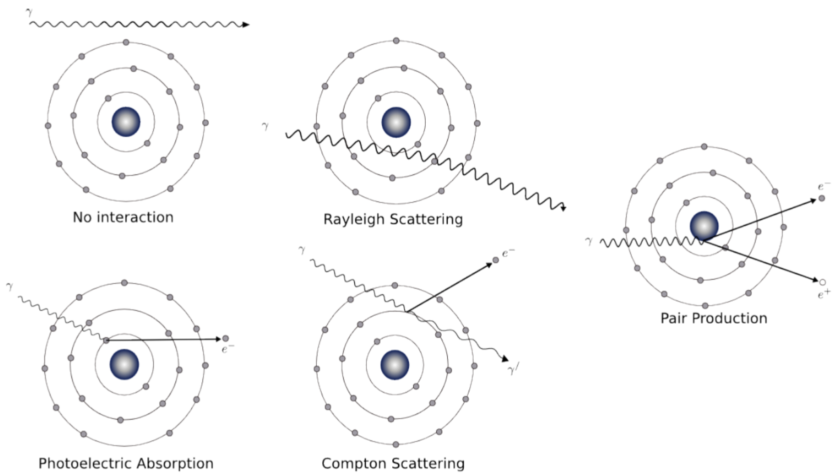


Fig. 4. Principles of photon-matter interactions

X-ray Material Interaction

> ⚠ The X-ray photons either experience a complete absorption, elastic scattering or inelastic scattering

- The reduction of radiation intensity is a reduction of the number of photons that arrive at the detector.
- That process is usually referred to as attenuation.
- There are several different physical effects contributing to attenuation, including a change of the photon count, photon direction, or photon energy.

X-ray Material Interaction: Absorption

- Absorption is the main effect that contributes to X-ray imaging:

$$I = I_0 \cdot e^{-\mu x}$$

with x as the material thickness and μ as the absorption coefficient that is **dependent** from the photon energy!

> Assuming ray optics (not photons), the absorption and attenuation along a path from the source to a detector is an accumulated attenuation of all materials (composites, e.g.,with different μ_i values) withing the path!

X-ray Material Interaction: Absorption

[Hahn, Mary, DGZfP-Proceedings BB 84-CD , "A general approach to flaw simulation in..", CT-IP 2003]

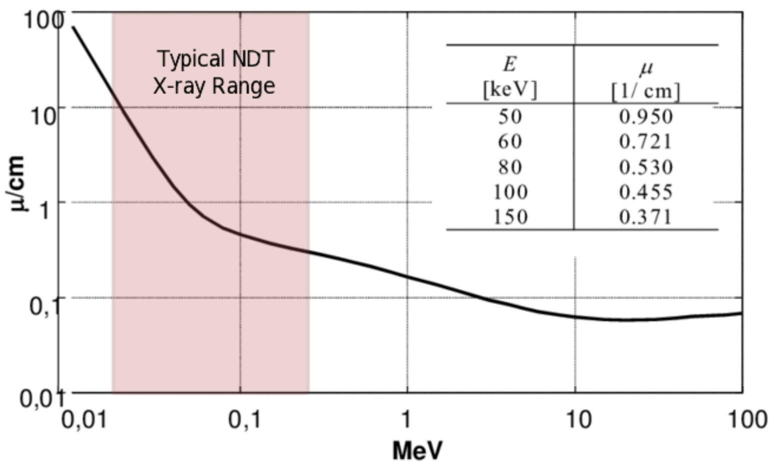


Fig. 5. Absorption coefficient μ for aluminum against X-ray energy

X-ray Measuring Technologies

> ⚠ We get intensity images, but want to have a material density images (Scanogram or Tomogram)!

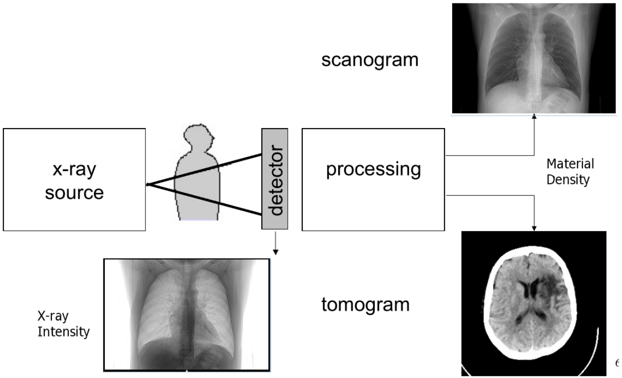


Fig. 6. X-ray image processing and output

X-ray Measuring Technologies

> ⚠ Material density can only be "reconstructed" from X-ray intensity correctly if monochromatic (discrete energy) radiation is used.

- Besides attenuation, there is scattering and diffraction related to very fine structures, lowering the density computation accuracy.

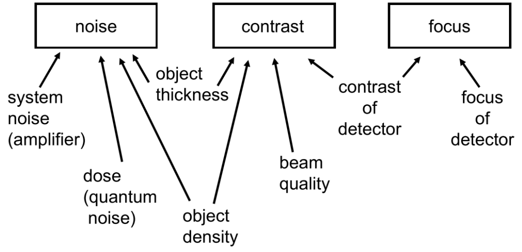


Fig. 7. X-ray image quality is influenced by multiple factors

X-ray Measuring Technologies

> ⚠ The Focal Spot Size Diameter (FSD) determines the maximal resolution of an X-ray imaging system!

[https://umsystem.pressbooks.pub/digitalradiographicexposure/chapter/focal-spot-size/]

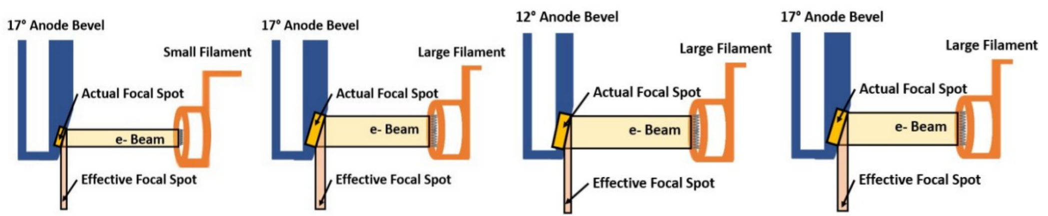


Fig. 8. The FSD depends on the filament size of the tube and the anode angle

X-ray Measuring Technologies

[https://umsystem.pressbooks.pub/digitalradiographicexposure/chapter/focal-spot-size/]

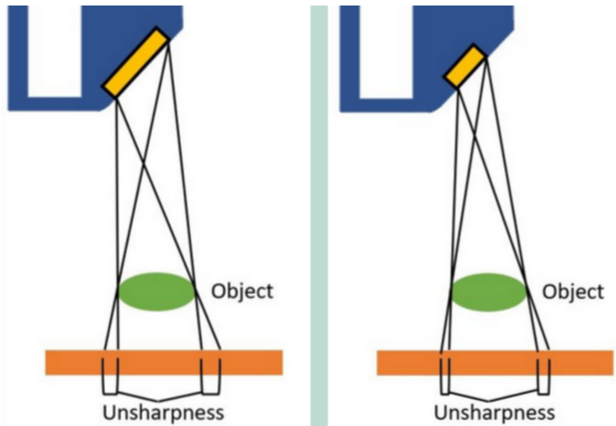


Fig. 9. Larger focal spot sizes increase penumbral unsharpness (but depends on magnification, too)

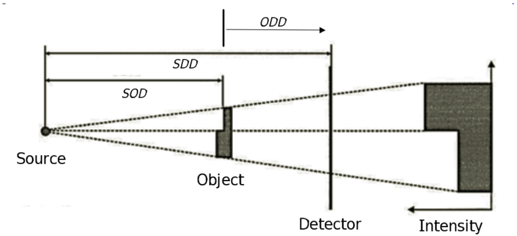
X-ray Measuring Technologies

> ⚠ The Source-Object (SOD) and Source-Detector (SDD) distances determine the image magnification *M* and the unsharpness *U*!

$$M = \frac{\mathrm{SDD}}{\mathrm{SOD}}$$

$$U = \mathrm{FSD}(M-1)$$

[Schiebold, Zerstörungsfreie Werkstoffprüfung – Durchstrahlungsprüfung, 2015]



X-ray Radiography

- Single projection measurement (central view)
- No in-depth information on structure
- Interpretation of images from multi-density composite materials is difficult

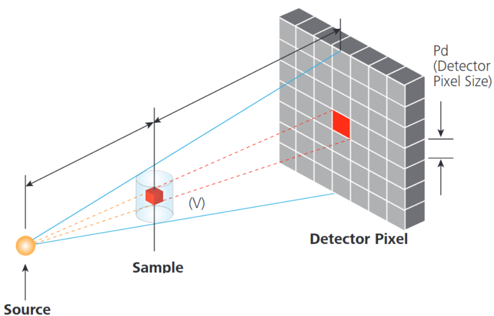


Fig. 10. Basic principle of radiography. [Zeiss] One (ray orthogonal) projection is captured providing an intensity image with intensities inverse proportional to the material density (and thickness)

X-ray Radiography

Effective maximal (theoretical) resolution R without unsharpness U is determined by the detectors pixel size p_{D} and the magnification M

$$R_{\mathrm{limit}} = \frac{p_D}{M}$$

X-ray Tomography

[Balasubramanian, Krishnamurthi, "X-ray scintillator lens-coupled with CMOS camera ..", PLOS Online, 2022]

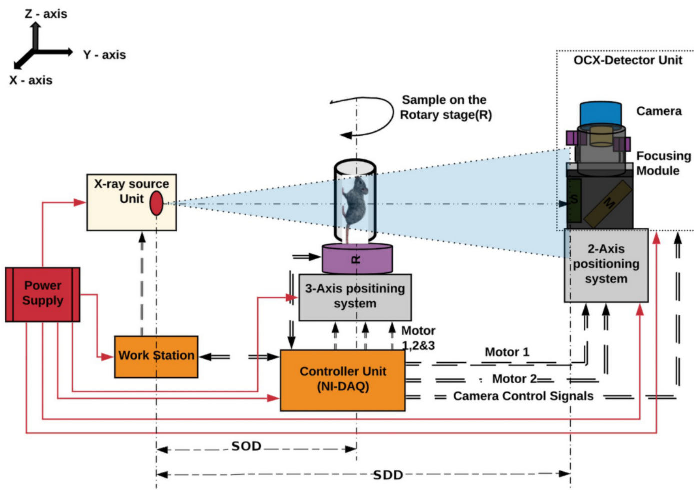


Fig. 11. Basic principle of Tomography capturing multiple projections (rotation) from the same specimen under different angles. Finally, a depth slice image stack is reconstructed from the rotation image stack.

X-ray Detection

⚠ At the end of the day we need a digital projection image, which is baed on an analog signal, which is based on electrons, which is based on photons!

There are basically three classes of X-ray detectors:

1. Semiconductors, direct electron generation by X-ray photons; CMOS or CCD camera;
2. Semiconductors, indirect electron generation by light photons and scintillator materials (X-ray → light); CMOS or CCD camera; no optics (except light guides)
3. Semiconductors, indirect electron generation by light photons and scintillator materials (X-ray → light); CMOS or CCD camera; with imaging or microscopy optics
4. X-ray Image Intensifiers (XRII), optics, camera

X-ray Image Intensifier

[Berger, Yang, Maier, Medical Imaging Systems, 2018]

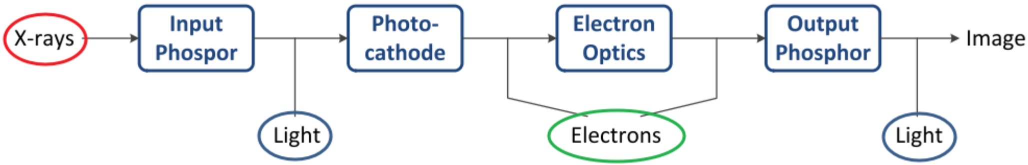
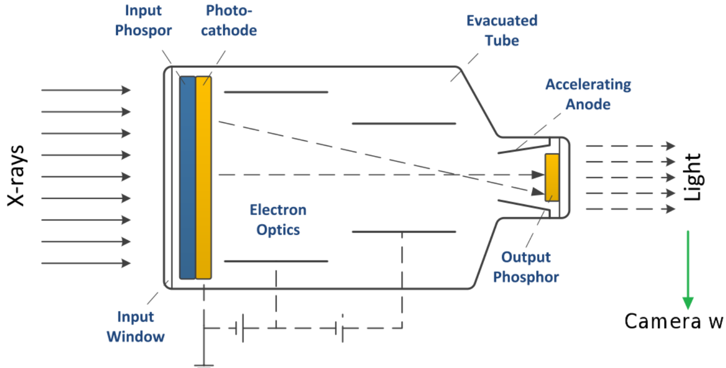


Fig. 12. Schematic principle of an image intensifier detector. The X-rays are first converted to light, which is converted to electrons. An optic accelerates the electrons towards a fluorescent screen which converts the electrons to light, which eventually results in an image.

X-ray Image Intensifier

[Berger, Yang, Maier, Medical Imaging Systems, 2018]



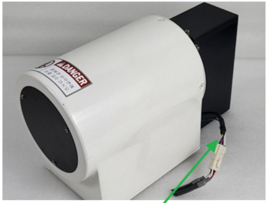


Fig. 13. Detailed principle of an image intensifier detector. The X-rays are first converted to light, which is converted to electrons. An optic focuses the electron beam to a fluorescent screen or film material which converts the electrons to light

X-ray Image Intensifier

> ⚠ The XRII itself and the following camera optics introduce geometrical distortions of the recorded images!

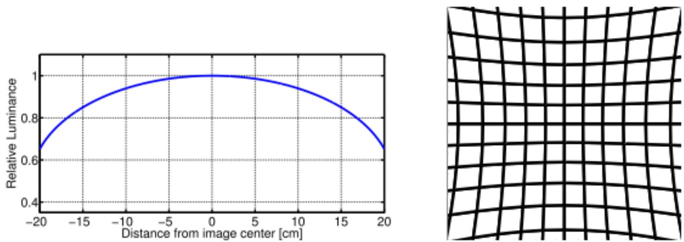


Fig. 14. (Left) Vignetting artifact, i. e., luminescence drops at image periphery (Right) Distortion artifacts due to external fields, field inhomogeneities and optical systems

X-ray Image Intensifier

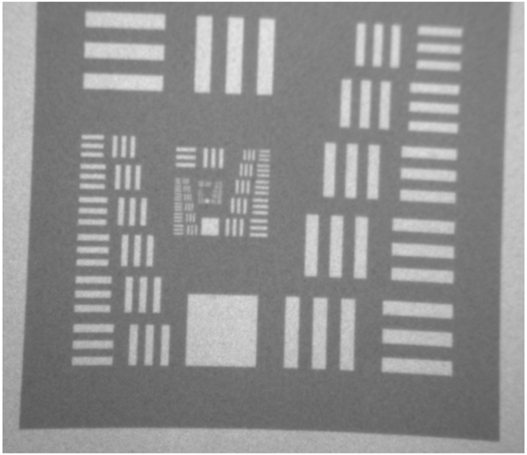


Fig. 15. Example image (USAF 1951 test target, steel foil 100μm) from a cheap OV2940 CMOS camera with mini lens optics using a Thales XRII (8"), 55kV, Tungsten X-ray tube (FSD 0.8mm)

X-ray Image Intensifier

Advantages:

- High sensitivity
- Medium area (about 10000 mm^2)
- Medium resolution, about 4 LP/mm

Disadvantages:

- Expensive
- High voltage generators required (up to 30 kV)
- Geometrical distortions (can depend on environmental conditions, external fields, ...)
- Sensitivity degrades during radiation exposition irreversible!

X-ray Images: Geometrical Errors

Besides common limitations that all imaging systems share, e. g., spatial resolution and contrast ratio, image intensifier systems are most known for vignetting and distortion artifacts. Vignetting,

Errors by:

1. Rotation
2. Translation
3. Skewing
4. Barrel distortion
5. Pincushion distortion
6. Any non-linear, an-isotropic and inhomogeneous distortions

X-ray Images: Geometrical Errors

[http://m43photo.blogspot.com/2012/05/geometric-distortion-correction.html]

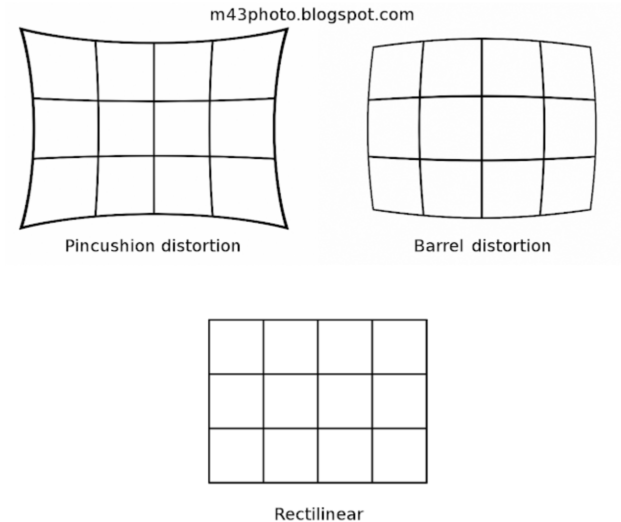


Fig. 16. Barrel vs. pincushion distortions

X-ray Images: Geometrical Errors

- Corrections by various algorithms and methods
- Commonly using a reference set of points (Ground truth points) and affine or non-linear polynomial transformation
- Fisheye Distortion Correction

Affine Transformations

[https://neutrium.net/mathematics/basics-of-affine-transformation/]

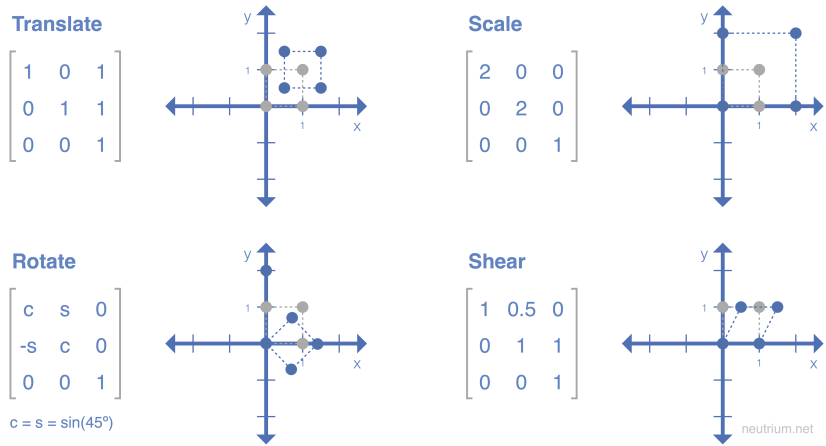


Fig. 17. Affine transformations are typically applied through the use of a transformation matrix ***M*** and its inverse ***M***$^{-1}$

Affine Transformations

For example to apply an affine transformation to a three dimensional point, P to transform it to point Q we have the following equation:

$$Q = MP$$
$$P = M^{-1}Q$$

- When dealing with affine transformation points are represented as $P = (P_x, P_y, P_z, 1)$ while vectors are represented as $v = (v_x, v_y, v_z, 0) = v = (v_x, v_y, v_z)$.
- Where multiple transformations are to be performed a single compound transformation matrix can be computed.

$$M = M_2\, M_1$$
$$M^{-1} = M_2^{-1}\, M_1^{-1}$$

Affine Transformations

Translation and Scaling

$$M_{\text{trans}} = \begin{pmatrix} 1 & 0 & 0 & m_x \\ 0 & 1 & 0 & m_y \\ 0 & 0 & 1 & m_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$M_{\text{scale}} = \begin{pmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Camera Calibration

- Using: [https://euratom-software.github.io/calcam/html/intro_theory.html]
  - Rectilinear Lens Distortion (RLD) Model
  - Fisheye Lens Distortion (FLD) Model

The RLD model takes in to account radial (barrel or pincushion) distortion, and tangential (wedge-prism like, usually due to de-centring of optical components) distortions.

The fisheye distortion model only includes radial fisheye distortion.

> ⚠ Problem: Point coordinate transformations can leave holes (uncovered target pixels). Interpolation is required!

Camera Calibration

RLD Model

$$\begin{pmatrix} x_d \\ y_d \end{pmatrix} = \left[1 + k_1 r^2 + k_2 r^4 + k_3 r^6\right] \begin{pmatrix} x_n \\ y_n \end{pmatrix} + \begin{pmatrix} 2p_1 x_n y_n + p_2\left(r^2 + 2x_n^2\right) \\ p_1\left(r^2 + 2y^2\right) + 2p_2 x_n y_n \end{pmatrix}$$

where $r = \sqrt{(x_n{}^2 + y_n{}^2)}$, and k_n and p_n are radial and tangential distortion coefficients, respectively. The polynomial r^2 in in the first term describes the radial distortion while the second term represents tangential distortion.

Camera Calibration

FLD Model

$$\begin{pmatrix} x_d \\ y_d \end{pmatrix} = \frac{\theta}{r}\left[1 + k_1\theta^2 + k_2\theta^4 + k_3\theta^6 + k_4\theta^8\right]\begin{pmatrix} x_n \\ y_n \end{pmatrix}$$

where $r = \sqrt{(x_n{}^2 + y_n{}^2)}$, and $\theta = \tan^{-1}(r)$.

X-ray Images: Geometrical Errors

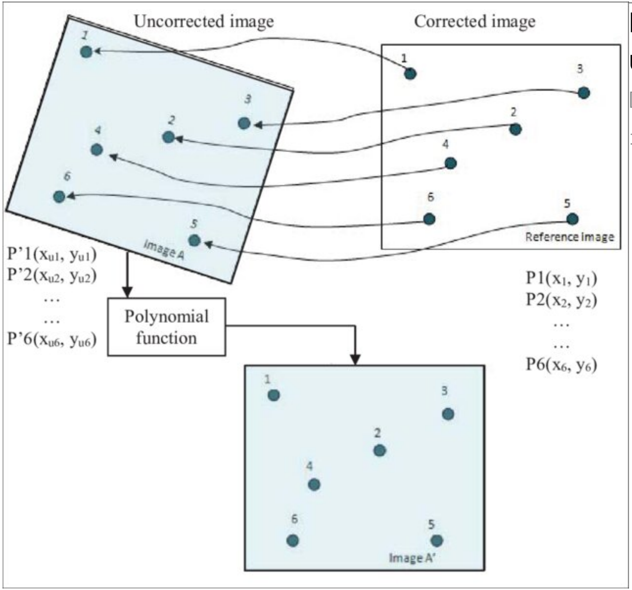


Fig. 18. Geometric corrections using polynomial functions

[Abdul Basith, 2011, DOI: 10.13140/RG.2.2.35707.00806]

X-ray Detector: Flat Panel

[Wotirz, Digital X-ray Sensors, Circuir Cellar, 2012]

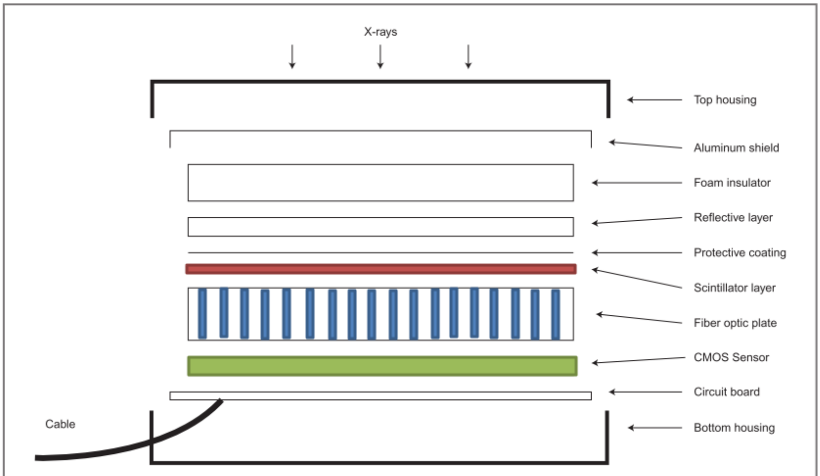


Fig. 19. Principle construction of a flat panel X-ray detector with a scintillator material, a light guide (fibres), and a CMOS/CCD image sensor

X-ray Detector: Flat Panel

Advantages:

- Nearly no geometrical distortions
- Moderate sensitivity
- Large area (about 250000 mm^2)
- High or medium resolution, real pixel size about 50-200 μm (theoretical resolution limit), up to 30 LP/mm

Disadvantages:

- Expensive
- Practical and theoretical resolution differs (especially in lower cost systems, far away from film-based imaging!)
- Noise (including X-ray induced noise)

X-ray Detector: Optical Screen Imaging

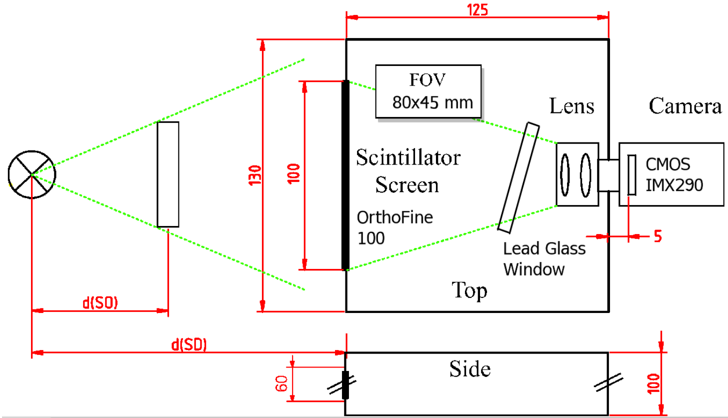


Fig. 20. Self-made low-cost X-ray screen imaging detector (Bosse, 2023)

X-ray Detector: Optical Screen Imaging

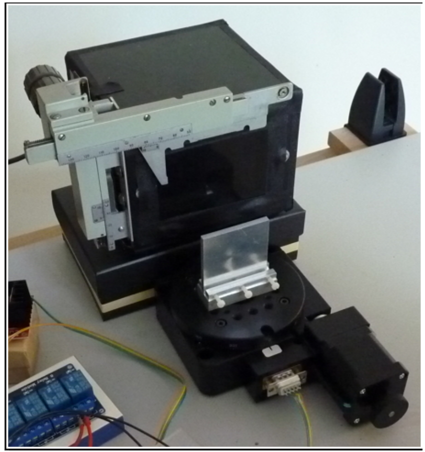


Fig. 21. Self-made low-cost X-ray screen imaging detector (Bosse, 2023)

X-ray Detector: Optical Screen Imaging

- Scintillator Screen: OrthoFine 100 foil (for medical radiography using films), green light emission
- CMOS image sensor: Sony IMX290 1920x1080 pixel (monochrome), exposure time 100-5000 ms
- Resolution limit: $3x3\mu m \times M_{opt}=13 \Rightarrow 40\mu m$

X-ray Detector: Optical Screen Imaging

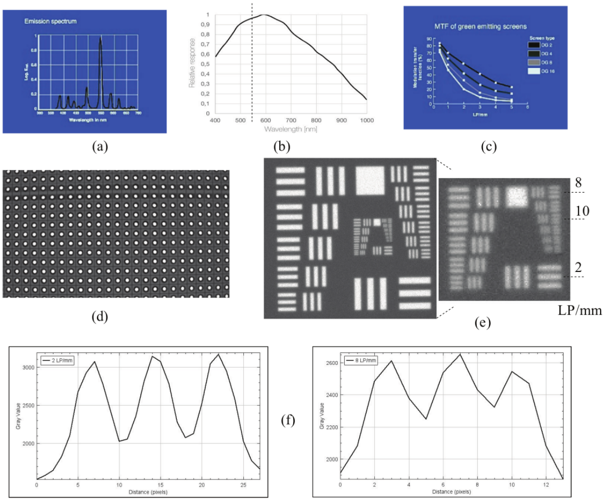


Fig. 22. Some recorded samples, contrast, and spectral light emission of scintillator versa camera sensitivity

X-ray Detector: Optical Screen Imaging

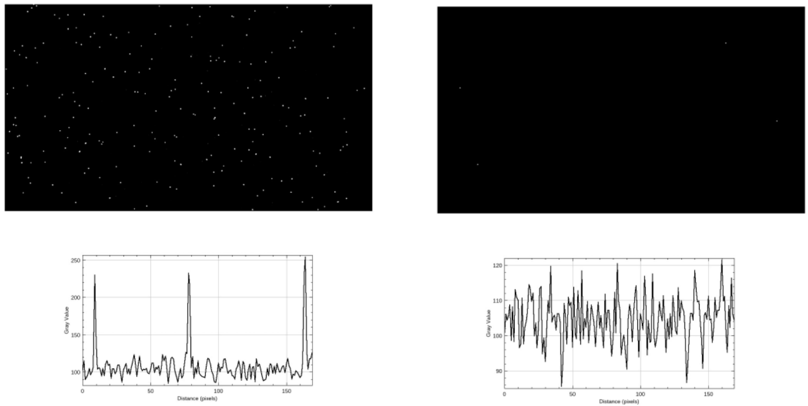
Advantages:

- Inexpensive
- Using only widely available components
- Medium area (about 4000 mm^2)
- Medium resolution, real pixel size about 10-50 μm, up to 10 LP/mm

Disadvantages:

- Geometrical distortions (but known and independent from environmental parameters)
- Noise (including X-ray induced noise)
- Low sensitivity, long exposure times
- Lead glass placed before detector introduces additional geometric distortions

X-ray Detector: Optical Screen Imaging



(a) Without Noise Cancellation

(b) With Noise Cancellation (2 Im.)

Fig. 23. The optical imaging system is sensitive to "popcorn" noise induced by incident radiation (even a mirror do not eliminate such kind of noise due to scattering). Algorithmic noise cancellation is required by using multiple images.

X-ray Noise

There are two types of undesirable effects in imaging systems: probabilistic noise and artifacts (+ distortions).

- Similar to noise, artifacts are image degradations that also find their source in physical effects during the scan.

However, the difference to noise is that when a scan is repeated using the exact same object and scan parameters, artifacts are reproduced exactly whereas noise effects will change based on a probabilistic scheme (and can be reduced/removed).

X-ray Noise

[Berger, Yang, Maier, Medical Imaging Systems, 2018]

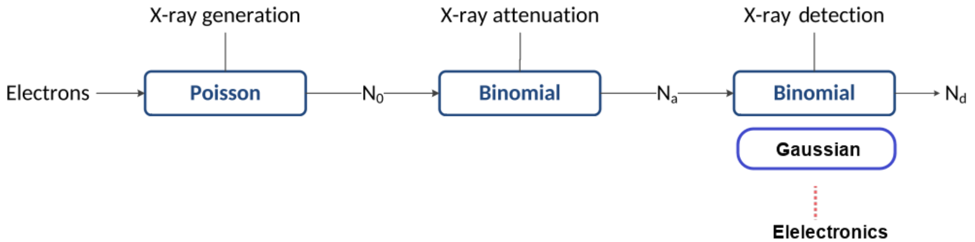


Fig. 24. Overview of noise related processes in X-ray imaging

A common quality measure for imaging is the signal-to-noise ratio (SNR).

In X-ray imaging it makes sense to use the definition based on statistics, i. e.,

$$\mathrm{SNR}(x) = \frac{\overline{x}}{\sigma} = \frac{E(x)}{\sqrt{E\left(\left(x - \overline{x}\right)^2\right)}}$$

For random variables *x* following a normal distribution (Gaussian), $\overline{x}$ is the mean value and σ represents the standard deviation.

X-ray Noise: Popcorn Cancellation

```
σ0 := Σ[1]
∀ (x,y) ∈ coord(σ0) do
  if σ0[x,y] > γ then
    ∀ σ ∈ { Σ / σ0 } do
      if σ[x,y] < γ then
        σ0[x,y] := σ[x,y]
        break
      endif
    done
  endif
  ∀ σ ∈ { Σ / σ0 } do
    if σ[x,y] < γ then
      σ0[x,y] := σ0[x,y] + σ[x,y]
    else
      σ0[x,y] := σ0[x,y] + σ0[x,y]
    endif
  done
  σ0[x,y] := σ0[x,y] / |Σ|
done
```

Alg. 1. Popcorn noise cancellation using multiple images (γ is a threshold, Σ a set of images, σ a pixel value)