

Computed tomography of biological samples

Measurement with the X-ray image sensor

Objects of the experiment

- Understanding the material absorption of the X-rays.
- Understanding the 3D-image reconstruction used for the computed tomography.
- Device adjustment and graphical tools for biological tissue identification.

Principles

The initial intensity I_0 of an X-ray beam is reduced after passing through a homogeneous material according to the Lambert law

$$I_s = I_0 e^{-\mu s}. \quad (1)$$

Here is I_s the resulting beam intensity, s the length of the way through the material and μ the material absorption coefficient. The latter has the physical dimension 1/Length and is material specific, depending a.o. on the material density, atomic number and the energy (wavelength) of the beam. Absorption coefficient reveals therefore material distribution, knowledge of which is of a great importance in medicine and other fields.

For inhomogeneous materials the constant absorption coefficient μ is replaced by $\mu(s)$ and the exponent in eq. (1) becomes an integral

$$\ln \frac{I_s}{I_0} = - \int_0^s \mu(s') ds'. \quad (2)$$

For a general absorption coefficient $\mu = \mu(x,y,z)$, given as a function on the three dimensional space, the integral in eq. (2) is written as a path integral

$$\ln \frac{I_s}{I_0} = - \int_0^s \mu(x(s'), y(s'), z(s')) ds' \quad (3)$$

along the straight beam path. For a fixed plane Σ (in the three dimensional space) parametrized by a coordinate system (x',y') , any line is given by the slope m and the y' -intersect b . For a function $\mu(x',y')$ on the plane Σ the integral along the line given by (m,b) is a functional assignment

$$(m,b) \mapsto \int_{-\infty}^{+\infty} \mu(x', mx'+b) dx', \quad (4)$$

called the Radon transformation. According to the Radon's theorem (J. Radon (1917)), the function $\mu(x',y')$ can be reconstructed if function's integral is known for all (m,b) .

Computed tomography (CT) is a direct application of Radon's theorem. According to eq. (3) a line integral of the absorption coefficient μ along the beam path in a sectional plane of a body is given by the logarithm of intensity fraction. Measuring therefore intensity fraction for many lines, absorption coefficient μ can be reconstructed. Its graphical representation reveals the sectional plane compound structure. Substance identification with application to medicine is studied in experiments P6.3.8.3-4 and P6.3.8.13-14. A CT measurement scheme is shown in fig. 1. Intensity fraction measurement for many lines is realized by the rotation of the body.

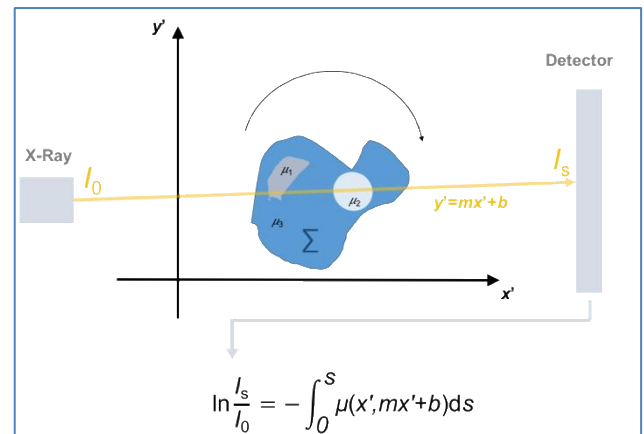


Fig. 1: A schematic representation of a CT-scan. Different colors mark different values of μ in the sectional plane Σ .

Measurement time restricts the number of rotation angles. A high-pass filter is therefore applied to measured data before reconstructing μ . A high-pass filter highlights boundaries of different materials (like bones and organs in a human body) as it amplifies the contrasts. It reduces therefore errors caused by the finite number of measurements. This procedure is called the *filtered Radon back transformation* and is the key of the CT algorithm.

The number of rotations and the used high-pass filter influence image quality and its resolution. The resolution is also restricted by the pixel size of the detecting device. A further source of image quality error is the continuous X-ray spectrum. Eq. (1) holds only for the monochromatic beam. Passing through material the X-ray beam spectrum is shifted to higher energies. This effect is called beam hardening and is studied in experiments P6.3.8.4 and P6.3.8.14. Absorption coefficient values in the whole body are obtained by combining measured data for different sectional planes. In this case the smallest image unit is called a voxel. Graphical representation of μ is the end result of the computed tomography.

The 1979s Nobel Prize in Physiology or Medicine was awarded to Allan M. Cormack and Godfrey N. Hounsfield for their development and application of computed tomography.

Devices

- 1 X-ray apparatus554 800
 - 1 Goniometer554 831
 - 1 X-ray tube, Au554 866
 - 1 Computed Tomography Pro package554 820P
- additionally required:
- 1 PC with Windows XP/Vista/7/8/10 (x86 or x64)

In this experiment a CT scan of a frog is done. Using CT software's graphical tools, spatial tissue distribution in the frog, like bones, muscles and even skin, can be visualized. This is a CT's big advantage compared to a single X-ray image, from which only hard materials, like bones und metals, are seen. Furthermore, students learn device adjustment, sources of errors and resolution restrictions.

Setup

- Insert the Au tube in the X-ray apparatus.
 - Put the dual-link DVI cable through the hole in the X-ray experiment chamber.
- a) Outside of the X-ray apparatus:
- Connect the dual-link DVI cable's end with the sensor's USB module. Connect the latter with power supply.
- b) Inside of the X-ray apparatus:
- Mount the goniometer in the X-ray experiment chamber and move it to the right side. Fix the goniometer using the two screws in its lower part.
 - Put the precision rails for X-ray image sensor into the experiment chamber.
 - Mount the X-ray image sensor onto the precision rails.
 - Connect the dual-link DVI cable with the X-ray image sensor.
 - Connect the X-ray apparatus and the X-ray image sensor to the PC using USB cables.

Image sensor adjustment

Note

Image sensor adjustment must be performed prior to the measurement.

- Turn off the X-rays (fig. 3: 2).
- Identify defective pixels and correct (fig. 2: 6 and 7).
- While X-ray beam and high-voltage are off (fig. 3: 2) create an offset image using dark frames (fig. 2: 6). Average over app. 10 images and use the offset image.
- Turn on the X-rays (fig. 3: 1).
- Record a white image averaging over app. 10 images and use this as a reference image (fig. 2: 7).
- Turn on the PC and the X-ray apparatus.
- Start the CT software and find the expandable tabs on the left.
- Choose the video device (fig.2: 3) and turn it on (fig. 2: 1).

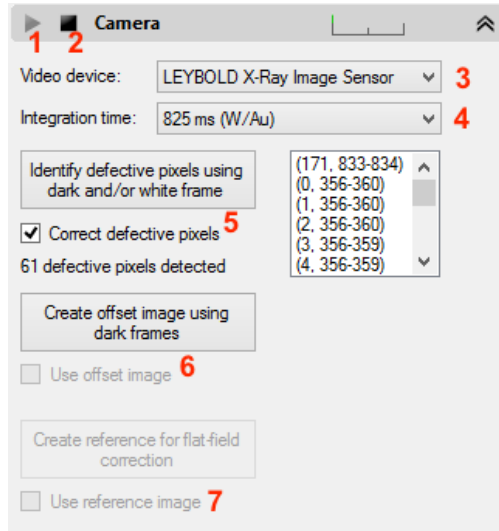


Fig. 2: Video device settings: 1: Device on, 2: Device off, 3: Choose video device, 4: Choose video input, 5: Choose average time, 6: Identify defective pixels, 7: Correct defective pixels,

Rotary axis adjustment

Note

Rotary axis adjustment must be performed after every device setup.

- Mount the LEGO® adapter into the goniometer.
- Combine five LEGO® bricks together and mount these on the LEGO® adapter in its middle.
- Close the X-ray apparatus and turn the on the high voltage.

In the now visible X-ray image of the LEGO® bricks, the prolonged rotation axis should appear horizontal in the middle of the image and coincide with the red line. In case of clearly seen misalignment turn off the X-ray radiation and make a rough image sensor adjustment. Use the screws around the camera inside the CT module to tilt and roll. Turn on the X-rays and the image sensor. Carry out a measurement keeping all settings as shown in figs. 2 – 4 by clicking on the button.

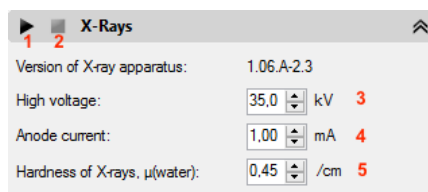


Fig. 3: X-ray setting: 1: X-ray on, 2: X-ray off, 3: High voltage, 4: Anode current, 5: X-ray hardness.

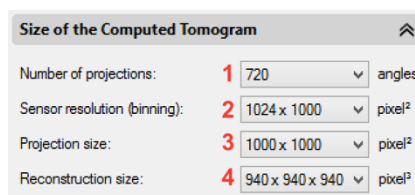


Fig. 4: CT size setting: 1: Number of projections, 2: Sensor resolution, 3: Projection size, 4 Reconstruction size.

After the measurement the X-rays are switched off automatically. Perform the following steps:

- Change to the 2D view by clicking on the **2D** button in the upper toolbar.
- Move the slider in the bottom to the **left** until a sectional plane close to the upper end of LEGO® bricks is shown on the screen.
- Vary the rotary axis value (fig. 6: **1**) until the double contours are roughly minimal (fig 5: **b**).
- Press “1st position” button (fig. 6: **2**) and wait until the software optimizes the position.
- Move the slider in the bottom to the **right** until a sectional plane close to the LEGO® bricks’ bottom is shown on the screen.
- Vary the rotary axis value (fig. 6: **1**) until the double contours are minimal (fig. 5: **b**).
- Press “2nd position” button (fig. 6: **3**) and wait until the software optimizes the position.
- Turn off the X-rays and adjust sensor position using the screws in a way the CT software suggest (fig 5: **4** and **5**).

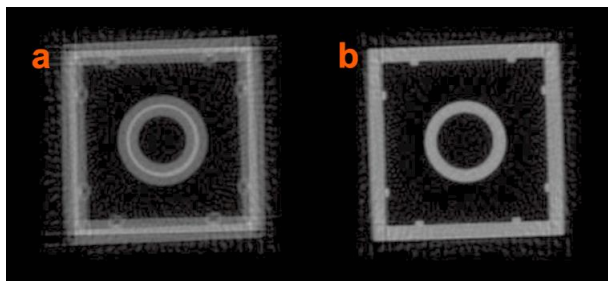


Fig. 5: Rotary axis adjustment: **a**: double contours, **b**: no double contours – the correct position.

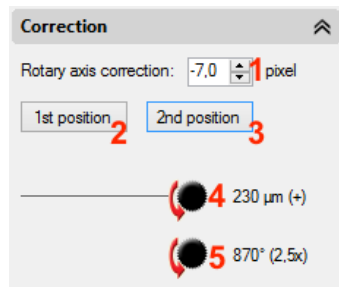


Fig. 6: Correction: **1**: Rotary axis correction, **2**: 1st position, **3**: 2nd position, **4-6**: suggested camera position adjustment.

Carrying out the experiment

- Carry out the upper steps for the image sensor and the rotary axis adjustment.
- Increase the number of projections (fig. 4: **1**) to 360 or higher depending on the graphic card.
- Unmount the LEGO® bricks from the LEGO® adapter and mount the frog instead.
- Carry out a measurement keeping all other settings as shown in figs. 2 – 4.

During the measurement, the image reconstruction can be observed in 2D as well as in 3D mode. Use the **2D** and the **3D** buttons in the upper toolbar to change modes. The image is gradually getting better as more and more angular steps are done and taken into account in the Radon transformation.

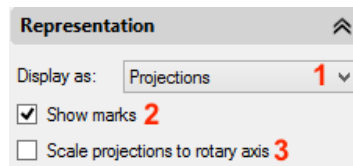


Fig. 7: Representation: **1**: Displays as, **2**: Show/Hide Marks, **3**: Scale projections to rotary axis.

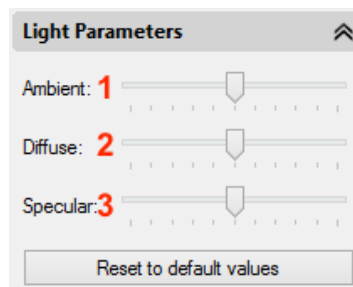


Fig. 8: Light parameters: **1**: Ambient, **2**: Diffuse, **3**: Specular.

In 2D mode image representation can be changed between “Projection”, “Log projection” and “Filtered log projection” (fig. 7: **1**). In this way we can visualize the difference between the standard X-ray image and the filtered projections used for the CT image reconstruction.

Evaluation

A detailed description of the software is available in the instruction sheet. Please see the manual for catalogue number 554821. Use buttons in CT software’s the upper tool bar to activate different modes and tools.




a) 2D and 3D modes

Use the **2D** and the **3D** buttons in the upper toolbar to switch the modes.


In 2D mode it can be changed between different sectional planes. Use the slider in the bottom. Change displays between “Projection”, “Log projection” and “Filtered log projection” (fig. 7: **1**). In this way it can be distinguished between the standard X-ray image and the filtered projections used for the CT image reconstruction. The sectional planes in 2D mode are orthogonal to the rotary axis.

In 3D mode the image of the scanned object can be rotated and observed from different view angles. Use the slider in the bottom to change between different sectional planes. In contrast to 2D view, sectional planes shown in 3D mode are orthogonal to the observer’s looking direction and parallel to the screen respectively


b) Arbitrary sectional plane

Use the  button in the upper toolbar while in 3D mode to change the representation between the selected sectional plane or the selected sectional plane and the rest of the scanned object behind it. If the  button is active, the sectional plane shown on the screen can be chosen for radiographic evaluations by clicking on the  button.

c) Colour spectrum

Use the  button in the upper toolbar 5 different colour spectra can be chosen. Different colours highlight different absorption coefficient values. Different materials appear thus in different colours. Some of the colour schemes are better suited to colour blind users.


d) Switching light on

Use the  button to turn on a virtual light source, which amplifies the CT-scan's 3D impression. Expand the "Light Parameters" (fig. 8) to change settings.

e) Intensity and transparency

In the "Intensity and Transparency" tab (fig. 9) different representation options can be set up. The upper slider (fig.9: **1**) changes the image intensity while the lower slider (fig.9: **2**) changes the transparency. If the transparency is set to a high level, then all soft tissues appear transparent. In this way tissues like bones can be visualised. Additionally, μ values can be restricted to a desired range. Use the sliders in the bottom of the "Intensity and Transparency" tab (fig.9: **3 - 4**). In this way only a certain tissue will be shown. This useful for tumours identification or single organs analysis.

f) Stereoscopic view

An even stronger 3D effect is achieved by activating the stereoscopic view with the  button. The image in this mode must be viewed through the anaglyph (red-cyan) glasses.

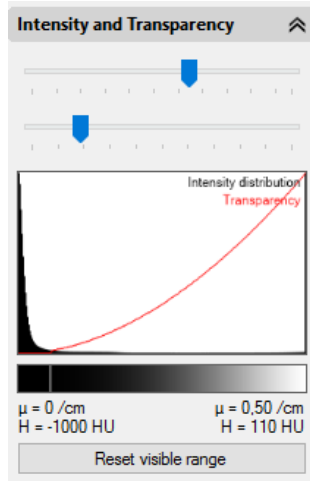


Fig. 10: Low transparency mode. The visible range is not restricted.

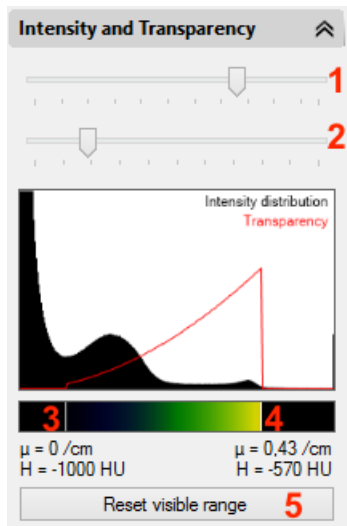


Fig. 3: Intensity and transparency: **1**: Intensity, **2**: Transparency, **3**: Lower transparency limit, **4**: Upper transparency limit, **5**: Reset settings.

Measuring example

Soft tissues and surfaces are visualized in the low transparency mode (fig. 10). Fig. 11 shows a frog's CT example for this setting with the full visible range. A virtual light source (right column) highlights surface shaping.

Hard tissues are visualized in the high transparency mode (fig. 12). Fig. 13 shows a frog's CT example for this setting with the full visible range. A virtual light source (right column) highlights surface shaping.

Soft tissues inside a hard envelope (like bone marrow) can be visualized in the low transparency mode, restricting the visible range to low μ values (fig. 14).

Fig. 15 shows a frog's CT example for this setting with the visible range restricted to low μ values. A virtual light source (right column) highlights surface shaping. In the case of the frog, an empty skin envelope appears on the screen.

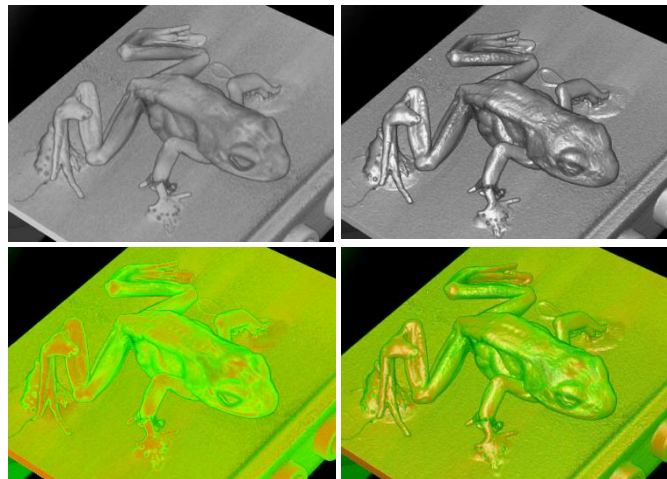



Fig. 11: Frog's CT scan with low transparency level (fig. 10). Right column includes a virtual light source (is activated using the  button).

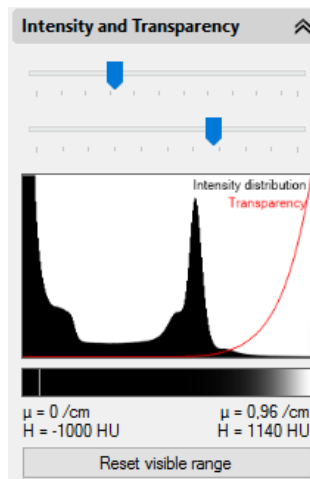


Fig. 12: High transparency mode. The visible range is not restricted.

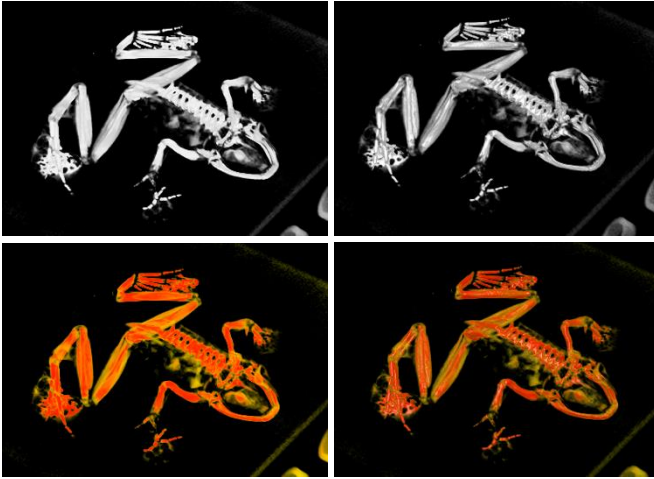



Fig. 13: Frog's CT scan with high transparency level (fig. 11). Right column includes a virtual light source (is activated using the  button).

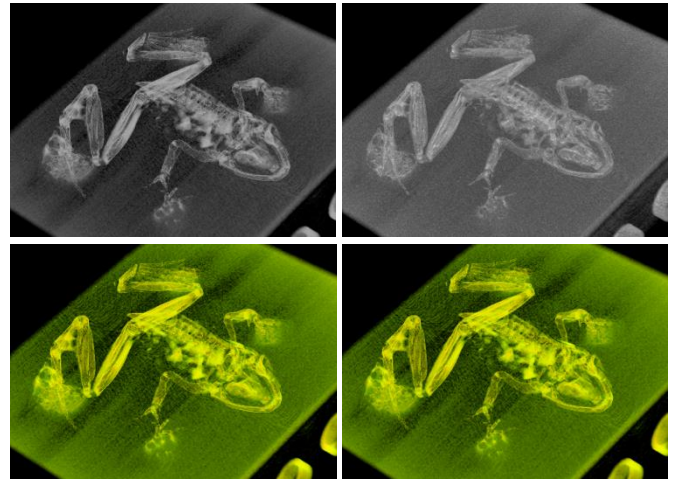



Fig. 15: Frog's CT scan with low transparency level and visible range restricted to low μ values (fig. 14). Right column includes a virtual light source (is activated using the  button).

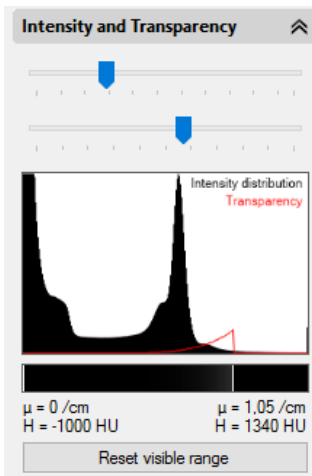


Fig. 14: Low transparency mode. The visible range is restricted to low μ values.