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Advancing learned algorithms for 2D X-ray computed tomography

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Citation

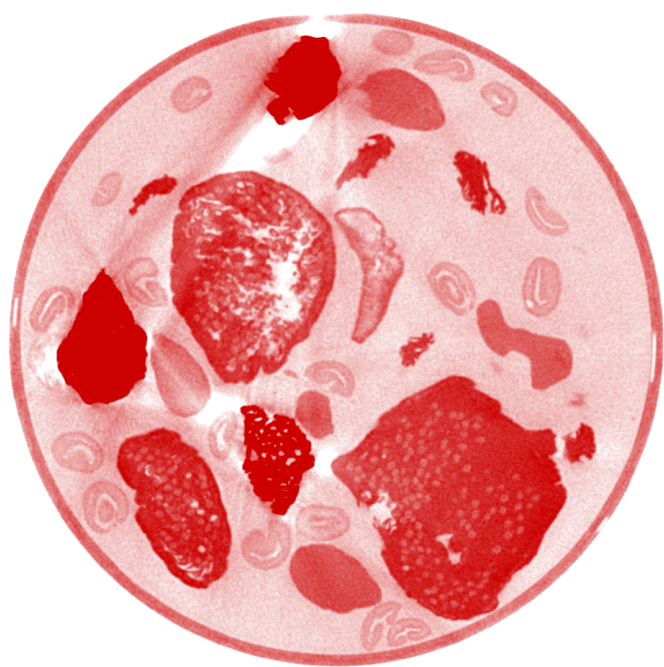
Kiss, M. B. (2025, November 7). *Advancing learned algorithms for 2D X-ray computed tomography*. Retrieved from <https://hdl.handle.net/1887/4282439>

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Tailoring CT Acquisitions in the FleX-ray Lab

One important concept of this thesis is tailoring CT acquisitions to the scanning samples. The relevance and impact of this concept is illustrated in more detail in chapter 3 for two cultural heritage case study objects. In this section, we present the specific laboratory CT scanner used for the experiments conducted in this thesis. The FleX-ray scanner is a custom-built, highly flexible X-ray CT scanner, developed by TESCAN XRE NV [216] located in the FleX-ray Laboratory at the Centrum Wiskunde & Informatica (CWI) in Amsterdam, The Netherlands. Generally, this laboratory is used to conduct proof-of-concept studies in the field of mathematics and computer science [43].

2.1 Functionalities of the FleX-ray scanner

The scanner has three main components: i) a cone-beam microfocus X-ray point source emitting polychromatic X-rays between 20 keV and 90 keV with a tube current between 10 μA and 1000 μA ; ii) a rotation stage, on which samples of different sizes (up to 40 cm $\times$ 40 cm $\times$ 40 cm) can be mounted; and iii) a CMOS (complementary metal-oxide semiconductor) flat panel detector with a CsI(Tl) scintillator (Dexella 1512NDT, [131]) with 1536 $\times$ 1944 pixels, 74.8 μm^2 each, onto which the X-rays are projected. The offset counts (“dark currents”) and the maximal readout of this detector are given by $\sim 1,000$ and 65,535 counts respectively. Translation stages enable all three components to move independently from one another. An image of the scanning set-up is shown in Figure 2.1.

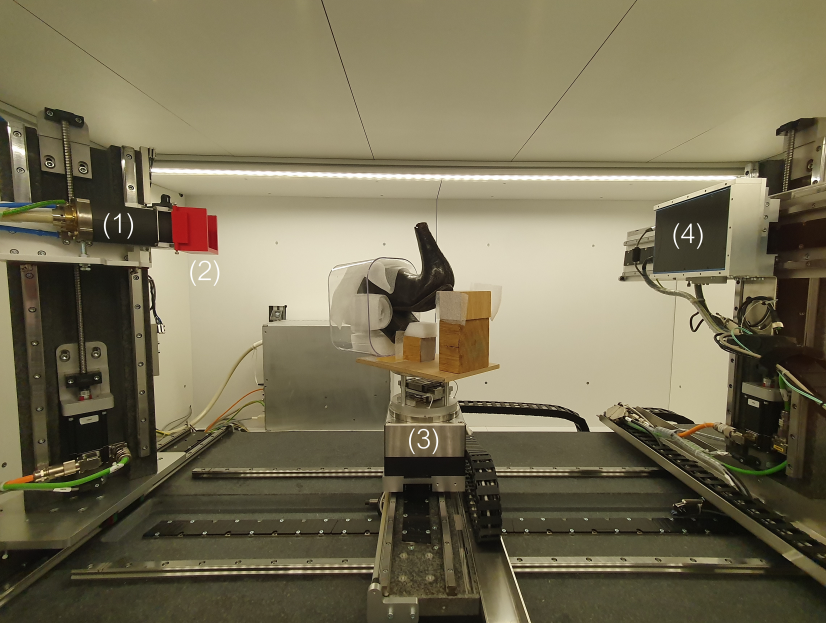


Figure 2.1: FleX-ray scanner setup with X-ray source (1), attached beam-filter holder (2), rotation stage with mounted object (3), and flat panel detector (4).

The main features of the FleX-ray scanner: X-ray voltage and current, motor movements for source, detector, and sample positioning, as well as detector features can be programmed for the full duration of a scan. These technical specifications, also listed in Table 2.1, enable better suited data acquisition and were instrumental to realize the CT scans in this thesis.

2.2 Extensions to the FleX-ray scanner

Although the FleX-ray scanner by itself already was a highly flexible micro-CT scanner, its operation required at times less reproducible and provisional research practices. To standardize and unify, for example, the positioning on the sample stage two extensions to the FleX-ray laboratory were created: sample stage disks and sample stage cylinders. Furthermore, the functionalities of the scanner were extended to use beam filtration for the CT acquisition by creating a beam filter holder and a set of exchangeable and combinable beam filter frames.

2.2.1 Sample stage disks

The rotation stage within the FleX-ray scanner is made of aluminium and has a sample stage disk made of aluminum as well placed on top of a carved out ring-like area. The

Table 2.1: Technical specifications of the FleX-ray scanner, HW: Hardware, SW: Software

Parameter	Value
Tube voltage	20 - 90 kV
Tube power	2 - 50/90 W ("microfocus" / "high power")
Tube current	10 - 1500 μ A (depending on the focus mode, standard 100)
Exposure time	11.7/14.3/38.5 - 5000 ms (dependent on hardware binning)
Number of frames to average	free choice in full integers
Hardware binning	1×1 (HW1SW1); 2×2 (HW2SW1); 4×4 (HW4SW1) HWX $X \times X$ pixels are grouped to SWY $Y \times Y$ pixels on the software side
Detector rows	1536 ($ROI = 1520; 8 - 1527$)
Detector columns	1944 ($ROI = 1912; 32 - 1943$)
Physical detector size	145.9 mm $\times$ 114.9 mm
Source Object Distance (SOD)	ca. 15 mm - ca. 1009 mm
Source Detector Distance (SDD)	ca. 139 mm - ca. 1098 mm
Magnification Factor $\alpha = \frac{SDD}{SOD}$	1.087 - 73.133
Number of projections	free choice in full integers, usually multiples of 360 +1 are used: e.g. 1, 361, 721, 1081, 1441, 1801, 2161, 2521, 2881, 3241, 3601

diameter of this ring on which the aluminium sample disk is placed was measured to be 110mm and we produced several additional aluminum disks. We produced 10 disks with a plain top surface for basic scans that require no exact positioning or mounting within the rotation stage diameter. They can also be taped to wooden boards, sponge materials or anything else that might be necessary for mounting the respective sample for the CT scan. Furthermore, 10 disks with a special design were created. They feature a sketch of angle markers and circles of different radii for exact positioning. At designated locations there are also holes to fit in LEGO™ studs or poles for exact positioning (cf. Figure 2.2).

2.2.2 Sample stage cylinders

When acquiring a CT scan, we also want to limit the number of scattered photons in our projections. One source of this unwanted scattering is the rotation stage within the FleX-ray scanner which is made out of aluminium. This scattering can be circumvented, though, by elevating the sample a few centimeters above the rotation stage. For this we used the diameter of the ring on which usually the aluminium sample disk is placed and 3D-printed cylinders with this diameter with varying heights and designs on the top surface (cf. Figure 2.3).

The motivation for varying heights comes from the fact that, depending on the region of interest that we want to use for both the object and the detector, we need a higher sample stage cylinder to prevent the metal rotation stage to be within the field-of-view or too closely adjacent. We created three different designs which are available in heights of 20, 50, and 100mm. The first design features a plain top surface for basic

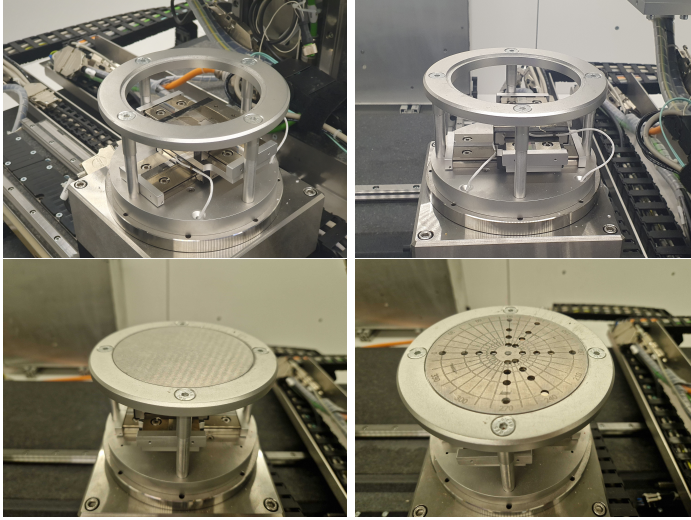


Figure 2.2: The rotation stage within the FleX-ray scanner with the two new sample stage disk designs (left: plain, right: with markers and holes).

scans that require no exact positioning or mounting within the rotation stage diameter. The second design encompasses a carved out volume of area $6.38\text{cm} \times 6.38\text{cm} \times 0.32\text{cm}$ (LxWxH) to fit in a LEGO™ base-plate of 8×8 studs. The third design re-models the design of the second sample stage disk and contains the same sketch of angle markers and circles of different radii for exact positioning including the holes at designated locations. These holes always reach half-way through the different heights of the sample stage cylinders.

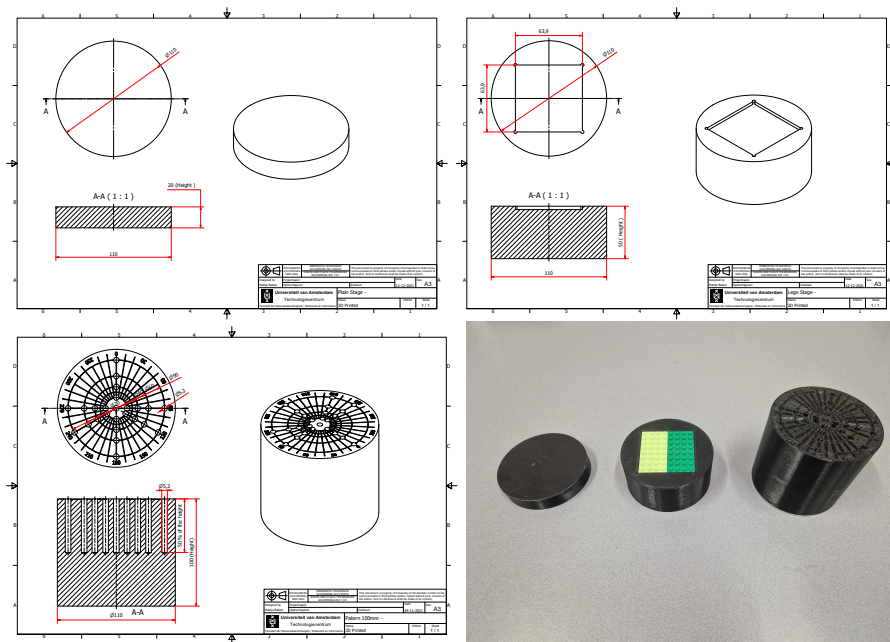
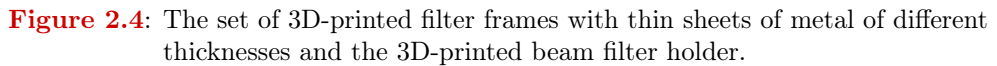


Figure 2.3: Technical sketches and 3D-printed realization of the three different heights and design choices for the sample stage cylinders.



As described in section 1.2, the interplay between a broad beam spectrum and the energy-dependent absorption of the sample's materials can create a range of image artifacts. With so-called beam filtration, the placement of materials into the X-ray beam, we can modify the X-ray spectrum and reduce its low-energy portion which is commonly referred to as "pre-hardening the beam". This shifts the mean photon energy towards higher energies and narrows the standard beam spectrum for CT imaging. It can minimize image artifacts due to beam-hardening and avoid saturation of the detector.

To enable a stable, exact, and reproducible beam filtration for the FleX-ray scanner, we designed a tool that can be mounted on the X-ray tube and allows for the placement of various filters into the beamline. This tool should hold the filters in a fixed position and allow also the use of multiple filters of different thicknesses and materials.

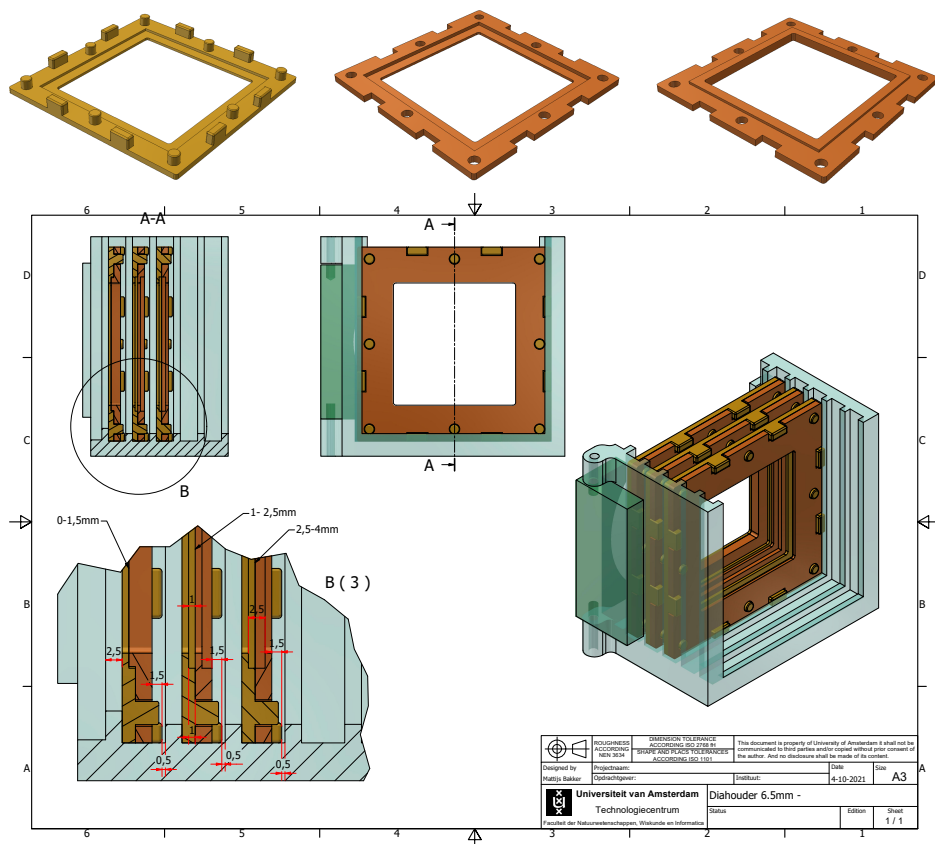


Figure 2.5: Technical sketches of filter holder and filter frames.

We designed a 3D-printed beam filter holder similarly to a slide projector with five slits. The corresponding filter frames were designed so that they are always tightly positioned within these slits and can host filter materials with a thickness ranging between 0.1 and 4.0 mm. The technical sketches and 3D-printed realizations can be found in Figures 2.5, 2.4, and 2.6.

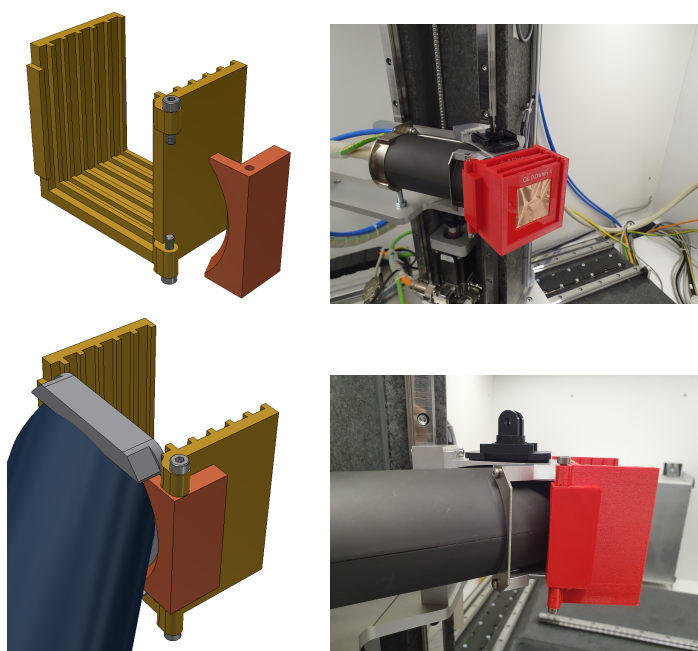


Figure 2.6: Setup of beam filter holder on X-ray tube.

2.3 Guideline for choosing suitable acquisition parameters

Setting up a CT acquisition for a chosen scanning sample can be an extensive and laborious task. Over the course of this PhD thesis, we developed a guideline for the FleX-ray scanner to help researchers with a step-by-step process to determine suitable acquisition parameters. Of course, some of the steps are more specific to our CT system and need to be adapted for a different system, but they might give the reader an initial idea and basic insight in how different choices influence the outcome of the CT acquisition.

We found four common basic objectives when scanning a sample: low noise, high angular and spatial resolution, high contrast, and fast scans. For a good signal-to-noise ratio it is important to consider how different acquisition parameters influence the noise level within the CT images such as source current, source voltage, exposure time, number of projections, and number of averaged images [172]. The number of projections necessary to have sufficient sampling and high angular resolution can be calculated considering the Nyquist-Shannon theorem with $P \geq \frac{\pi}{2} S$ [94]. Depending on the experiment, there might be limitations in the choice of one or multiple of the acquisition parameters, but it might be possible to compensate for these choices with adjusting other values.

As a prerequisite for applying the subsequent guideline, the minimal and maximal available values of the following three CT acquisition parameters should be known: tube voltage, tube current, exposure time. Furthermore, the dynamic range of the detector in use should be determined, namely the lower bound, given by the offset counts (“dark currents”), and the maximal readout of the detector (at FleX-ray Laboratory: $\sim 1,000$ and $65,535$ counts). This is done to identify the necessary photon flux for the CT acquisition. The aim should be to have counts of at least a two- to three-fold of the dark current at any location in all radiographs and never to saturate the detector.

1. Determine a suitable SOD and SDD to achieve the desired resolution in the CT reconstruction of the object under investigation. Use the intercept theorem: $\frac{voxelsize}{SOD} = \frac{detectorpixelsize}{SDD}$ to calculate the corresponding scaling factor $\frac{SOD}{SDD}$ and to determine whether the object under investigation can fit onto the detector with this geometry: $geometrydiameter = detectorwidth \times \frac{SOD}{SDD}$ as well as $geometryheight = detectorwidth \times \frac{SOD}{SDD}$. If the object does not fit, it might be necessary to acquire a tiled scan where multiple reconstructions are stitched together vertically or the detector needs to be placed at multiple positions and a bigger virtual detector is stacked together.
2. Empirically determine the rotational position with the lowest detector signal which corresponds to the largest attenuation in the line of sight. This usually corresponds to the thickest part of the object and/or where the object is composed of denser materials.

3. Investigate the minimal photon energy needed to penetrate the object in this rotational position by slowly increasing the tube voltage in small steps of e.g. 5kV while observing the minimal detector signal. The measured signal should be a two- to three-fold of the dark current (at FleX-ray Laboratory: 2000-3000 counts).
4. Choose adequate filtration that can filter out the low energy part of the spectrum, i.e. photons that have a lower energy than the energy found in the step above. The mean photon energy within the beam spectrum should be above the minimal penetration photon energy and also the minimal photon energy of the spectrum should be close to that. This may require to use a peak tube voltage (kVp) that is considerably higher than the tube voltage corresponding to the minimal photon energy. To find a suitable beam filtration for the object under investigation the corresponding beam spectra can be simulated with the TASMIP software [22]. For lower minimal photon energies thin sheets of Copper (e.g. 0.01 - 0.50mm) can be used whereas higher energies may require thin sheets of Tin (e.g. 0.10 - 0.50mm) or compound filters such as the Thoraeus filter of (e.g. Sn 0.25mm, Cu 0.5mm, Al 0.5mm) that can effectively filter out photons carrying an energy of 1.5 keV to 70 keV [93].
5. Exclude the K-edges of any metals within the object by adjusting the tube voltage accordingly. A list of absorption edges can be found, for example, at the following website [57].
6. Calculate the maximal feasible acquisition time per projection image of the detector from the total available scanning time to achieve the highest signal-to-nois-ratio (SNR) that satisfies the given time and saturation constraints. Also, consider taking multiple frames for averaging each projection, if the total available scanning time allows for that. The three important values for this are: First, the minimal feasible exposure time available determined by the electronics of the CT scanner / detector $t_{exp,min}$; second, the maximal exposure time restricted by the saturation of the detector $t_{exp,max-det}$; third, the maximal exposure time restricted by the total available scanning time $t_{exp,max-time}$. The second upper bound can be simply measured when moving the scanning object out of the field of view and radiating the detector with the previously found tube voltage, chosen beam filtration and the maximal tube current and increasing the exposure time from the minimal value until the detector saturates. The other upper bound can be calculated by the following formula:

$$t_{exp,max-time} = \frac{t_{total-image-series}}{(\#PPI + \#proj) * \#avg} \quad (2.1)$$

where the variables are given as:

- $t_{exp,max-time}$ - maximal exposure time restricted by the scanning time
- $t_{total-image-series}$ - available scanning time for the total image series

- $\#_{PPI}$ - number of pre-processing images which is the sum of all dark and flat field images (before+after)
 - $\#_{proj}$ - number of projections
 - $\#_{avg}$ - number of averages
7. Find a balance for the trade-off between the reduction of beam-hardening image artifacts, improved contrast, and reduced noise by adjusting the tube voltage and tube current within the given boundaries.

In this section, we have outlined the essential steps for setting up a CT scan and choosing suitable acquisition parameters such as SOD, SDD, tube voltage and current, beam filtration, and exposure time tailored to specific samples. By following these guidelines, researchers can effectively optimize their CT scanning outcomes while balancing factors like noise, resolution, contrast, and scan speed. Although some of the contents of this chapter are specific to the FleX-ray Lab, the extensions can be implemented in other laboratories as well and the structured approach above can foster a deeper comprehension of how varying parameters influence the CT scanning process.