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Technical Note

Introduction to Phase Contrast micro-Computed Tomography

What is micro computed tomography?

When an object is placed in front of an x-ray source, the shadows, or projections, of the object can be captured by a detector in the background. Computed tomography, also known as CT, is basically the process of reconstructing an image representation of the object from its x-ray projections using computer algorithms. The source-object distance (SOD) and source-detector distance (SDD) are two important physical parameters in the design of a micro-CT scanner.

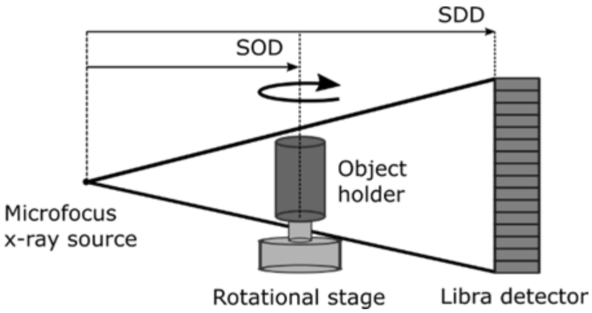

Figure 1: Illustration of a micro-CT scanner

Typical micro-CT parameters

Micro-CT systems come in all shapes and sizes depending on the applications. There are nevertheless some basic parameters that can quickly tell both designers and users the performance of a micro-CT scanner.

Spatial Resolution

Spatial resolution is commonly referred to as *image resolution*. It refers to how close images features can be to each other while still be distinguishable. There are different ways to quantify spatial resolution, one convenient and modern way is through the modulation transfer function (MTF).

Modulation Transfer Function

The modulation quantifies the relative amount the detected signal amplitude stands out from the background. This is a measure of *image contrast*. If we express how the contrast depends on feature size, we get a measure of spatial resolution. The MTF does exactly that by expressing the modulation as a function of spatial frequency.

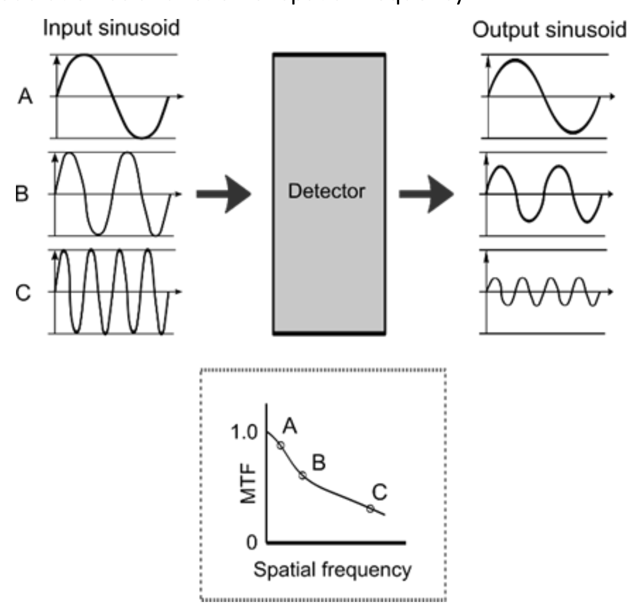

Figure 2: MTF: Measure of contrast capability as a function of spatial frequency [1]

Higher spatial frequencies correspond to smaller objects. As the spatial frequency increases, the detector has an increasing difficulty in reproducing the small features in the detected image because of inherent blurring present in the system. The MTF is equal to one (i.e. perfect contrast) at zero spatial frequency because it represents the background. By our definition of the modulation, all non-zero spatial frequencies are expressed relative to the background and in practice are less than one. A limit of detectability (e.g. 0.1, or 10% MTF) can be defined based on human observers.

[1] Even though the image is not an actual sine wave, it can be decomposed mathematically into sine and cosine components using the Fourier Transform. Thus, MTF is normally expressed in terms of attenuations of an image's spatial sinusoidal components.

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Detective quantum efficiency

While MTF may focus on image signal, our perception of features in an image is also affected by *image noise*. To take this into account, the detective quantum efficiency, or DQE, relates to the signal-to-noise ratio (SNR) in an image. The best SNR possible is the intrinsic photon SNR in the incident beam. The DQE reports the SNR in the acquired image, relative to this photon SNR. As such, an ideal detector has a DQE of one (i.e. no additional noise added through detection). The value of the DQE depends on the spatial frequency, or feature size, being considered. Because the MTF (signal) tends to decrease with increasing spatial frequency, the DQE will as well.

Voxel resolution

Also typically referred to as nominal resolution, this is the smallest possible volume element (i.e. 3D pixel) in the reconstructed volume. It is not a measure of spatial resolution, as features of that size may not actually be distinguishable in the (2D) image. The amount of available magnification will affect the nominal resolution.

Detectability

Detectability refers to the smallest feature that can be detected by a voxel. Again, this is not a measure of spatial resolution (e.g. the feature size may be smaller than the voxel itself). It is not only related to voxel resolution but also related to x-ray absorption of the material and the signal-to-noise ratio of the detector itself. As such, detectability will vary according to the type of material being imaged. Furthermore, a detector with a sufficient contrast compared to background noise will produce better detectability.

X-ray Detection Technique: Direct vs indirect

Digital x-ray detectors can be classified into either direct conversion or indirect conversion techniques. In either case, the digital image readout can be done through: crystalline Si (c-Si) charge-coupled device (CCD), amorphous silicon (a-Si) thin-lm transistor (TFT), or c-Si complementary metal-oxide-semiconductor (CMOS). CCD detectors are capable of real-time frame rates (i.e. 30 frames per second) with relatively low noise and a small pixel size but are limited in imaging area. The a-Si detector can be fabricated over large area which is required for full-field clinical radiology.

But a-Si detector inherently suffers from higher noise and has large pixels size (> 50 µm). CMOS imaging technology has emerged as a competitor to CCD detectors with comparably low noise, a similar scalability to very small pixel sizes, and higher frame rates. It is also compatible with standard CMOS processing allowing high levels of integration.

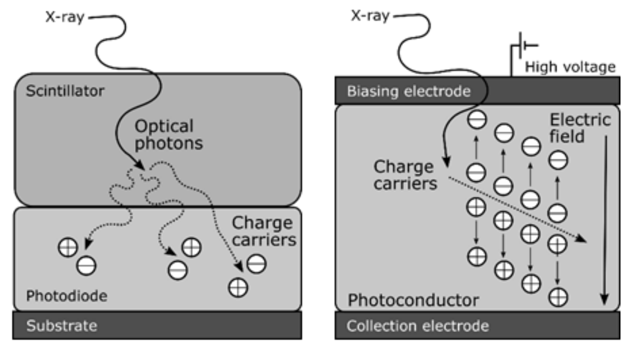

Figure 3: indirect (L.) and direct (R.) X-ray detection. Note that indirect conversion requires a scintillator to convert X-ray photons into charges

In indirect conversion, either a pixel-level a-Si/CMOS photodiode or CCD potential well is used to collect optical light generated by a scintillator such as CsI or Gd_2O_2S. The direct conversion method uses a photoconductor (e.g. a-Se, CdZnTe, HgI2, or PbO) to generate charge carriers by the photoelectric effect which are then collected under applied electric field. Conventional high spatial resolution scintillator-based detectors have poor absorption efficiency at high spatial resolutions due to thinning of the scintillator to minimize secondary optical scatter.

In direct conversion, the thickness of the photoconductor does not affect the spread of absorbed energy from X-ray interactions and the subsequent diffusion of photo-generated charge carriers during transportation is negligible. No significant degradation of spatial resolution occurs as the photoconductor thickness is increased for high brilliance applications. Nevertheless, the fabrication process for direct conversions has many technical challenges. Therefore, indirection conversion remains the standard method of X-ray detection in commercial CT systems.

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Factors affecting micro-CT resolution

Pixel size is not everything. Having a small pixel size is intuitively a criteria to achieve high resolution. However, achieving good contrast relative to noise is the key in micro-CT imaging, which is expressed through metrics like MTF and DQE. This allows us to distinguish small volumetric features and discriminate different materials. There are other components besides the detector in a micro-CT that can greatly influence the resolution as well.

X-ray source focal point and object placement

As shown in the figure below, if the size of the x-ray source focal spot is nearly a perfect point source, then there would be very little penumbra (unsharpness in the x-ray shadow). In this case, the physical pixel size of the detector gives the resolution limit, regardless of object position.

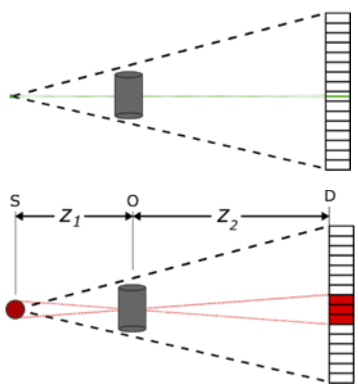

Figure 4: Effect of the object position on spatial resolution

In reality, the spatial resolution of an x-ray source is limited by the focal spot size σ_f that is not a perfect point. Through geometric magnification in the cone-beam imaging geometry, the detected focal spot size will be magnified: $\sigma_f(M-1)$, where $M=(Z_1+Z_2)/Z_1$, is a factor determined by the source-to-object distance Z_1 and object–to-detector distance Z_2. The increase in penumbra results in increased geometric un-sharpness in the object image. The equivalent blurring introduce to the object is $\sigma_g = \sigma_f(M-1)/M$. When the object is moved very close to the source, the blurring is solely dependent on focal spot size σ_f, while it is not at all dependent when the object is close to the detector.

The micro-CT x-ray source, detector, and geometric magnification should be optimized such that the system resolution is simultaneously higher than both the detector and the x-ray source spatial resolution.

Benefits of Phase Contrast for micro-CT

The primary advantage of the phase-contrast paradigm is that when an object presents poor conventional absorption-contrast (e.g. soft biological tissue or other low-density materials such as polymers), contrast can instead be generated with higher sensitivity using a variety of phase-contrast techniques. The major requirement is the ability to translate phase information to image contrast.

Traditionally, the conventional x-ray detector only measures x-ray intensity. To capture the phase information, specialized optical elements need to be added in order to convert the phase shifts into intensity. The use of grating interferometers is an example used in commercial phase contrast micro-CT. A more straightforward implement is to produce phase-contrast through simply free-space propagation. Free-space propagation can be used as a technique to render phase variations in the x-ray wavefront (in the presence of the object) visible as intensity fluctuations at the detector. This is done by resolving the interferences of the refracted object beam with the unaltered beam. The only requirement for propagation-based phase-contrast is a high resolution detector and large enough transverse spatial coherence length l_t, given by $l_t = \lambda Z_1/\sigma_f$, λ is the x-ray wavelength. A microfocus source should be used to achieve this if source-to-object distance Z_1 is physically constrained.

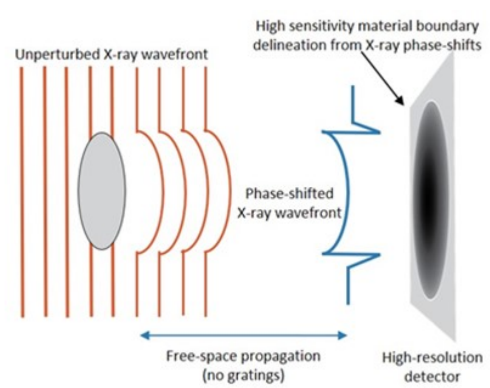

Figure 5: Propagation-based, grating-less phase-contrast.

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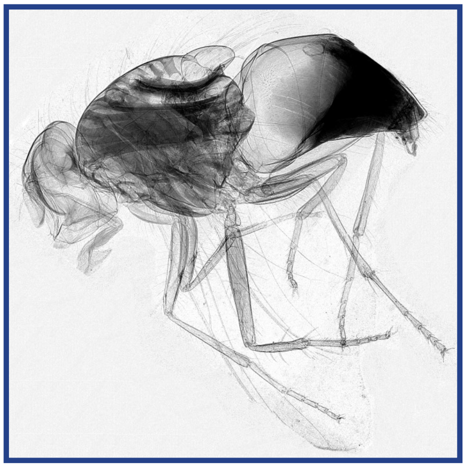
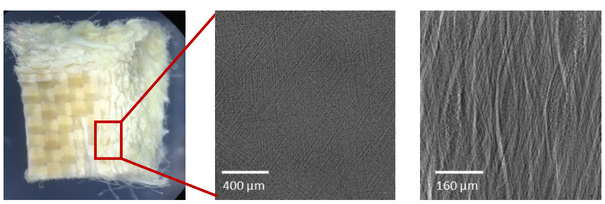
Micro-CT Applications

CT systems are commonly used in hospital as a medical imaging diagnostic tool. Micro-CT scanners can also have medical applications but by no means limited by it. The applications of micro-CT scanners can typically be classified into the following areas.

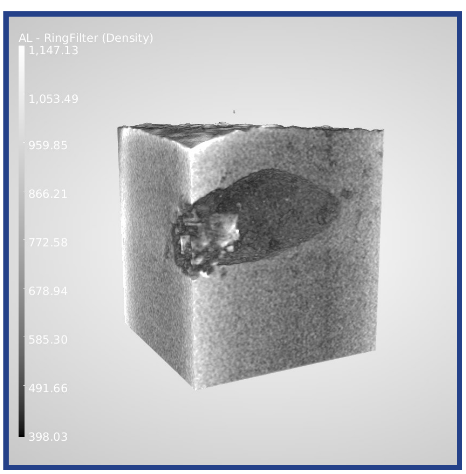
Life Sciences



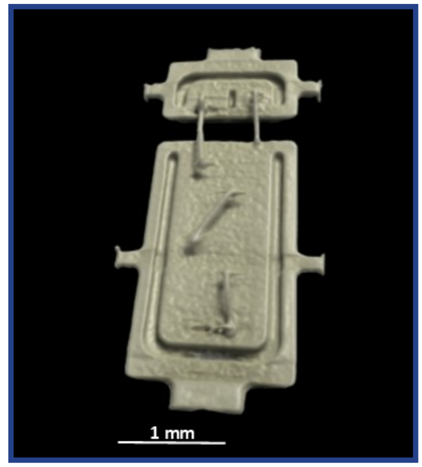
Material Analysis



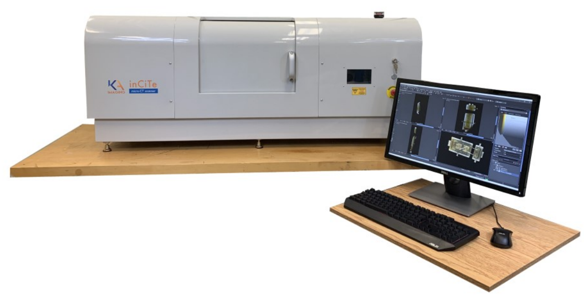
Non-destructive testing (NDT)



Quality Assurance



KA Imaging inCiTe™ micro-CT scanner with phase -contrast



Combining some of the best features in micro-CT scanner design, the inCiTe™ benchtop micro-CT scanner is the first commercial X-ray CT scanner that utilizes high spatial resolution a-Se detector technology exclusively developed by KA Imaging. The high conversion efficiency of the a-Se detector enables very high-speed sampling at low X-ray radiation dose. Owing to the high efficiency, unprecedented volumetric scan speed can be obtained at full resolution. In addition, the inCiTe micro-CT scanner is designed with patented propagation-based phase contrast imaging to enhance detail of fine structures that are typically X-ray transparent, without losses associated with grating-based phase contrast systems.

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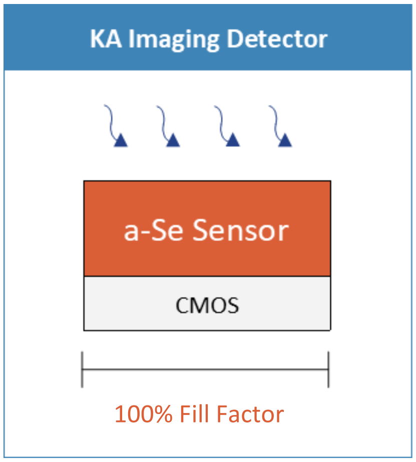

Figure 6: inCiTe™ micro-CT with direct conversion amorphous-Selenium detection technology

Moreover, the InCiTe micro-CT is equipped with a high quality micro-focus X-ray source to achieve unparalleled resolution. Integrated software controls and simplified user interface enable a high degree of automation and reduce operator dependence. The size and weight of the inCiTe micro-CT scanner are designed for minimum footprint, ease of transportation, and convenient integration into laboratory benchtop stations. The novel micro-CT scanner features efficient, high resolution X-ray imaging in a compact benchtop system. Below is an overview of inCiTe™ unique features.

Unique Features	Description	Advantages
Type of detection	MTF = 30% at 64 cycles/mm, 60 kV	• 100% fill factor • Up to 100x more efficient than scintillator type detectors
Pixel Characteristics	8 µm, 16 MP	• 1.4 µm true spatial resolution with maximum magnification • 0.8 µm nominal resolution at maximum magnification (2 µm focal spot source)
Phase Contrast	Propagation-based	• Bigger detection range (40-100 kV) vs. grating-based system
Contrast Detection	MTF = 30% at 64 cycles/mm, 60 kV	• Excellent small feature contrast imaging for polymers, and other low density materials

About KA Imaging

Founded in 2015, KA Imaging is a spin-off from the STAR group at the University of Waterloo. Our company has successfully developed a line of x-ray imaging products based on patented amorphous selenium process. The patented x-ray sensor technology represents the highest spatial resolution direct conversion X-ray detector in the world, with 100% fill factor and over 50% MTF at 45 even higher spatial frequency. Our main product offerings include benchtop micro-CT scanner, high resolution X-ray area detector for high brilliance coherent x-ray applications, and flat panel detector (FPD) for both medical and NDT applications.

References

C. Scott, *Hybrid Semiconductor Detectors for High Spatial Resolution Phase-contrast X-ray Imaging*, PhD Thesis, U of Waterloo, 2019

K. Karim *et al.*, High Does Efficiency, Ultra-high Resolution Amorphous Selenium/CMOS Hybrid Digital X-ray Imager, IEEE International Electron Devices Meeting, 2015