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Tutorial review

X-ray microtomography

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ABSTRACT

In this tutorial, we describe X-ray microtomography as a technique to nondestructively characterize material microstructure in three dimensions at a micron level spatial resolution. While commercially available laboratory scale instrumentation is available, we focus our attention on synchrotron-based systems, where we can exploit a high flux, monochromatic X-ray beam to produce high fidelity three-dimensional images. A brief description of the physics and the mathematical analysis behind the technique is followed by example applications to specific materials characterization problems, with a particular focus on the utilization of three-dimensional image processing that can be used to extract a wide range of useful information.

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1. Brief History and Evolution of X-ray Microtomography

The characterization of material microstructure is typically an exercise in trade-offs. The trade-offs centered around spatial resolution versus range of coverage, destructive versus nondestructive nature, degree of specimen preparation required, and availability of the characterization instrumentation. Microscopy, in its widely varying forms, can provide an extremely detailed picture of physical microstructure, but is limited to regions very close to the specimen surface. When coupled with micromachining techniques, such as focused ion beams, an excellent three-dimensional image can be constructed, at the cost of destroying the specimen. X-ray microtomography (also frequently referred to as micro CT) is a radiographic imaging technique that can produce 3D images of a material’s internal structure at a spatial resolution better than 1 micrometer. The specimen preparation is typically minimal, and for many materials the technique is nondestructive allowing many scans to be made of the same specimen under different conditions. The technique is complementary to higher resolution 2D microscopy and lower resolution 3D ultrasonic imaging. In this tutorial review, we wish to introduce the reader to the technique and the potential applications. For greater depth and breadth, we refer the reader to more comprehensive works (e.g. [1]).

X-ray microtomography has its roots in Computerized Axial Tomography (CAT or CT) scans that have been used for medical imaging for 40 years [2,3]. CAT scans were an extension of conventional projection radiography, a technique that can readily (given a sufficiently powerful source) produce a two-dimensional image of an object’s internal structure. In these images, broken bones or tooth decay can easily be identified because of the variations in X-ray absorption seen between bone and the surrounding tissue. The problem with the technique is that features can only be located within the

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two-dimensional plane of the image. The position of a tumor, or some other feature of interest, cannot be located out of the plane of the image. Furthermore, a 2D radiograph image presents us only with average X-ray absorption through the object’s out-of-plane dimension. A feature can be completely missed because it overlaps with other competing features through the depth.

CT scans solve these problems by combining information from a series of 2D X-ray absorption images recorded as the object is rotated about a single axis. (Note that rotation is relative. In fact medical scanners hold the object stationary while the X-ray source and detector are rotated about the object.) Using mathematical principles of tomography, this series of images is reconstructed to produce a three-dimensional digital image where each voxel (volume element or 3D pixel) represents the X-ray absorption at that point [4]. Because of the relationship between X-ray absorption and material density, the 3D internal structure can be inferred from the images, and internal features can be uniquely positioned. The resulting 3D images are typically displayed as a series of 2D "slices". The process is schematically illustrated in Fig. 1.

While most early applications of computerized tomography were for medical imaging, the benefits of true three-dimensional maps of internal structure led to rapid adaptation of the technique in other fields, including materials science. Specialized industrial CT scanners were produced that were capable of imaging materials of greater density than human tissue.

Over the years, conventional CT scanners employed X-ray tube sources in which electrons are accelerated and allowed to collide with a target producing bremsstrahlung radiation. Acquisition of 2D radiographs required appropriate scintillation, to convert the X-rays to visible light, and photodetectors to produce a digital image. Earlier CT scanners used a linear array of photodetectors, which meant tomographic slice images had to be acquired and reconstructed one plane at a time (fan beam, Fig. 2). Subsequent application of 2D detectors allowed the acquisition of 2D projection images (cone beam, Fig 2), leading to faster scan times.

The spatial resolution of conventional CT systems is typically limited by the geometry of the X-ray beam along with the characteristics of the detector. As illustrated in Fig 3, for a point source (fan beam or cone beam) the spot size of the X-ray source plays an important role. The smaller the spot size, the smaller the penumbral blurring, which will help produce a more accurate the projected image. A larger spot size means that photons hitting a particular pixel can be traced back through different ray paths through the specimen. As detailed below, this adds significant noise to the tomographic reconstruction. For this reason, commercial CT systems typically employ microfocus X-ray sources with spot sizes approaching a few micrometers or smaller. One megapixel detectors (e.g. 1024 by 1024) are routine, while some units boast 10+ megapixel detectors.

A significant development in micromotographic imaging was the use of synchrotron radiation as an X-ray source, which brought significant enhancements to the imaging that can be done [5–8]. Synchrotron radiation results from the bending of a high-energy electron beam due to a magnetic field. The emitted light is many orders of magnitude greater in brightness than that emitted by conventional X-ray sources. The implication for tomography is that the high flux allows one to resolve very subtle variations in absorptivity and therefore internal structure. The analog for this phenomenon could be the difference between taking a photograph in low light, where the resulting image can be grainy, and taking a photograph with an accompanying flash, where the resulting image has much higher contrast. Additional advantages of synchrotron radiation include X-ray beam collimation (the parallel beam shown in Fig. 2), which simplifies the tomographic reconstruction algorithm, and the tunability of the X-ray energy to a narrow energy band. As noted below, the use of a monochromatic X-ray beam improves the accuracy of the reconstructed tomographic images by eliminating the issue of energy dependence on X-ray absorption.

The high quality imaging capabilities of synchrotron radiation has led to an increasing number of available facilities around the world. Some of these facilities have stations dedicated to micromotography that are available to outside general users. It should be noted that in order to realize most of the advantages of synchrotron X-ray sources, imaging is typically limited to relatively small specimens, typically 5-10 mm.

Fig. 1 – Schematic illustration of X-ray CT acquisition and reconstruction processes. A series of X-ray projection images is acquired and mathematically reconstructed to produce a 3D map of X-ray absorption in the volume. The 3D map is typically presented as a series of 2D slice images.
Fig. 2 – Illustration of different X-ray CT acquisition configurations. (a) illustrates a fan beam, in which projection data must be acquired slice by slice. (b) and (c) illustrate cone beam and parallel beam configurations, respectively. In these configurations, complete 2D projections can be acquired in a single step. (d) illustrates the error associated with a non-point X-ray source. The intensity acquired at a particular point on the detector is made up of rays from different parts of the source that passed through different parts of the specimen, confounding the line-integral representation of the acquired intensity at the point.

Fig. 3 – Illustration of the incident and acquired X-ray represented as a ray passing through the object. (a) the acquired intensity $I(x,z)$ is modeled as a line integral of X-ray absorption along the ray path. Total absorption along the path is calculated through measurements of both $I_0$ and $I$. (b) to (d) show images that illustrate the stages of X-ray absorption measurement. (b) is a map of $I(x,z)$, (c) is a map of $I_0(x,z)$, and (d) is the corrected radiograph, $r(x,z)$, calculated using Eq. (2).
2. Underlying Physics of X-ray Microtomography

The basic principles invoked for CT imaging are the X-ray absorption physics, which is relevant for the 2D projection images, and the tomographic reconstruction mathematics, which is invoked when producing a 3D volume from the series of 2D projection images. We note that in this tutorial, we focus our attention on X-ray absorption tomography, recognizing that techniques such as phase contrast tomography can also provide valuable information.

For characterizing X-ray absorption, we note that the absorption of light as it passes through a material is a logarithmic function of the absorptivity of the material, and the distance through which the light must travel (here we assume a parallel X-ray beam traveling perpendicular to the image plane along the y-axis). The true absorptivity of the material depends on the number (density) and type of atoms along the path of the beam. The atomic absorptivity decreases as the energy of the X-ray photons increase (wavelength decreases), except in the vicinity of X-ray absorption "edges" which are characteristic of each atomic element. In general, for a fixed X-ray photon energy lower-Z (fewer electron) elements absorb less than higher-Z elements (with the absorption edges again being a complicating factor). Extensive tables of X-ray absorption coefficients (as a function of element number and X-ray photon energy) have been produced [9] and there are several online tools [10,11] that allow for good estimates of X-ray absorption to be made given a-priori knowledge of a sample's atomic makeup and density. Referring to Fig. 3a, the X-ray intensity I, measured at a point (x,z), can be related to the incident X-ray intensity, I₀(x,z), by:

$$I(x,z) = I₀(x,z)e^{-\tau}.$$  \hfill (1)

in which $\tau$ is the total X-ray absorption along the ray path, and can be mathematically represented as a line integral of absorptivity along the path defined by coordinates x and z. Assuming the incident and transmitted X-ray energy are measured quantities, the absorption is calculated by solving Eq. (1) for $\tau$:

$$\tau = \ln\left(\frac{I₀}{I}\right).$$  \hfill (2)

Experimentally, the intensities I and I₀ can be determined through the acquisition of the X-ray beam as illustrated in Fig. 3. Fig. 3b shows a raw projection image taken of a small Portland cement mortar specimen illuminated with synchrotron radiation. In order to measure the incident X-ray beam profile, I₀(x,z), the specimen is moved out of the field of view and capture a second image (Fig. 3c). This image clearly illustrates the spatial variability of the incident X-ray beam, as well as variations in the detector. Because the X-ray detector may have a baseline charge independent of the light striking it, a baseline image of a dark field is typically taken and subtracted from the incident and transmitted images. Hence, the absorption at a particular pixel located at position (x,z) is calculated by:

$$\tau = \ln\left(\frac{I₀-I_d}{1-I_d}\right).$$  \hfill (3)

in which I_d is the dark field intensity at that point. A resulting corrected radiograph is illustrated in Fig. 3d. For a typical tomographic scan hundreds of such radiographs are produced, each one representing a projection of the object at a different angle.

Once an accurate series of corrected radiographs are made of a specimen, the next step is a tomographic reconstruction. Details of the mathematics involved in tomographic reconstruction are beyond the scope of this tutorial; however, a brief overview of the topic is presented here. Referring to Fig. 4, in an arbitrary plane normal to the axis of rotation (z-axis), a 2D function f(z,y), is shown. A projection function, Lₐ(z',θ), can be created by a

![Fig. 4](image-url) - Illustration of X-ray absorption model used for tomographic reconstruction. In the x,y plane (normal to the axis of rotation) the object is represented by a spatial function of X-ray absorption, f(x,y). Any set of X-rays passing through the object projects an absorption profile Lₐ(z',θ) on an axis z'. This intensity profile is acquired (a single row of pixels in Fig. 3d) for each angle increment. A collection of these profiles for a particular slice at successive view angles, θ, is often represented a sinogram, as shown in (b), with a single line profile superimposed on the image.
series of line integrals evaluated along rays acting perpendicular to the axis $x'$.

$$L_2(x', \theta) = \int_0^1 f(x, y) \, ds.$$  \hspace{1cm} (4)

A projection radiograph created using Eq. (3) is simply a collection of these projection functions for a specific rotation angle $\theta$, with each horizontal row of pixels (x-axis) representing a different function $L_2(x', \theta)$. In the tomographic reconstruction process, these line functions are typically collected over all rotation increments for a particular row, $z$. This collection is referred to as a sinogram because of the shape of the path created by collections of relatively bright pixels over the different projection angles.

In tomographic reconstruction, we must solve an inverse problem in which $f(x, y)$ is determined from a series of projection functions. Mathematically, this problem was solved by Radon in 1917 [12] (translated by Parks [13]), who showed:

$$f(x, y) = -\frac{1}{2\pi^2} \lim_{\theta \to 0} \frac{1}{q} \frac{3}{\partial x} L(x \cos \theta + y \sin \theta + q, 0) \, dq.$$  \hspace{1cm} (5)

While uniqueness can be shown for a continuous $f(x, y)$, practical limitations complicate the solution process. Errors are introduced through both the discrete nature of the acquisition, and the imperfect nature of the measurement processes. Several types of reconstruction algorithm have been developed, including both direct and iterative solutions. Direct methods such as Filtered Back Projection (FBP) and Direct Fourier Inversion (DFI) are based on the "Fourier Slice Theorem" which essentially states that the Fourier Transform of a (1-d) projection is equivalent to a line or slice through the Fourier Transform (2-d) of the original object function. All of the reconstructed images in this paper were produced with either FBP or DFI algorithms.

Tomographic reconstruction is a computationally intensive process, and because of the commercial value of a fast reconstruction algorithm, many such algorithms are proprietary.

3. **Information Provided by Microtomography**

At a most basic level, a tomographic reconstruction of projection images provides us with a 3D map of X-ray absorption. Because different material features and phases often have different X-ray absorption properties, we can easily identify the different features from these images. For X-ray microtomography, the spatial resolution of these 3D maps or images can approach 1 micrometer. Fig. 5a illustrates this with an $xy$ tomographic slice image of the same mortar specimen for which a projection image is shown in Fig. 3b. The slice shown represents one of several hundred such slices of a complete volume measuring 800 by 800 by 600 voxels in the $x$, $y$, and $z$ directions, respectively. The three-dimensionality of the images is illustrated by the computer-rendered 3D image of Fig. 5b. Three-dimensional renderings are particularly effective for qualitative assessment of spatial relationships.

While the 2D slices and 3D renderings have significant qualitative value, perhaps the most compelling aspect of tomographic data is the digital nature of the 3D images. There is a wealth of literature on digital image processing (e.g., [14–16]), which can be exploited to extract a wide array of quantitative measurements on internal structure. As highlighted below, these measurements can include relatively simple characteristics such as phase volume fractions and phase connectivity, to more complex measurements such as spatial distributions, orientations, alignment, and connectivity of microstructural features. These types of measurements are illustrated in the examples that follow.

4. **Example Applications**

4.1. **Analysis of Phases**

The distribution of discrete phases in a material is of interest for a wide range of issues and applications that range from processing to bulk properties. Considering once again the 2D slice image of Fig. 5a, we can observe in generic terms, a

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**Fig. 5** – A sample reconstructed slice image (a), and a sectioned 3D rendering (b). In these images, the brightness is a function of X-ray absorption, with bright spots showing regions of high absorption, and dark spots showing regions of low absorption.
multiphase particulate composite made up of aggregate particles, a hydrated and unhydrated cement matrix, and pore space. The reason we are able to identify these different features is the aforementioned variation in X-ray absorption. This variation manifests itself through the different grayscale intensities in the images of Fig. 5, and appears to our eyes as the distinct phases they are. These images were made using synchrotron-based microtomography at a magnification that produced 6 micrometer cubic voxels.

An extremely valuable tool for phase analysis in 2D and 3D images is the voxel intensity histogram. As the name implies, the intensity histogram plots the frequency, or number of occurrences of voxels of a particular intensity. This is valuable because we can often use it to segment the image into the different phases. As illustrated in Fig. 6a, which shows a histogram for an 800 by 800 by 600 volume shown in Fig. 5b, distinct peaks are seen corresponding to air and solid phases. A simple segmentation is illustrated in Fig. 6b and c, where the black and white image of Fig. 6c was created from the grayscale image of Fig. 6b by setting all pixel values less than the threshold (about 80) equal to zero (black), and all values greater than the threshold to one (white). In this manner, the pore space is easily identified. A similar approach can be taken with other phases. For example, in Fig. 7, the specimen has been segmented according to the histogram of Fig. 7a, where the solid different solid phases have been approximated by the overlapping distributions shown. The separate solid phases: aggregate particles, the surrounding matrix of connected hydrates, and discrete unhydrated cement particles, are illustrated in the 3D renderings of Fig. 7c, d, and e, respectively. A more rigorous method of this type of analysis was developed by Otsu [17]. It should be noted that: in the example images and histograms shown, the data were down-sampled to an 8-bit intensity range from the floating-point representation produced by reconstruction. This is done primarily to reduce computer memory requirements during analysis. In doing this, one does run the risk of masking subtle differences in absorption. However, with proper attention to the meaningful data range (i.e. non-zero histogram values), the conversion to 8-bit can usually be done with minimal real affect on segmentation measurements.

The overlapping intensity distributions shown in Fig. 7a illustrate a potential problem with intensity-based segmentation. For the void-solid segmentation, illustrated in Fig. 6, the method is reasonably accurate because there is minimal overlap between the void and solid phases. In this case the measured amount of pore space is relatively insensitive to the specific choice of threshold as long as it is in the range where the intensities are minimum. For the segmentation problem shown in Fig. 7, however, there is much more uncertainty because of the overlapping intensities. For a material such as a cement-matrix composite, with mineral aggregates, the X-ray absorption levels are very similar among phases. Indeed, without the high flux provided by synchrotron radiation, the solid phases blend together into a relatively uniform shade of gray. When analyzing this kind of image, other methods must be employed, such as edge detection, gradients or local variance must be applied.

While the 3D renderings can be particularly useful for qualitative assessment of phase distribution, we again note that the digital nature of the data affords us opportunities for numerous quantitative analyses. Once a particular phase is isolated in an image, there is a whole array of quantities that can be measured. Many analyses start with what is called an analysis of connected components, or a connectivity analysis. In such an analysis, each voxel of a particular color (say black) is compared to all the surrounding voxels that share a face (6-connectivity), a face or an edge (22-connectivity), or a face, an edge, or a corner (26-connectivity) [18]. If any of the surrounding voxels are of the same color, they are considered to be part of the same object.
Fig. 7 - Segmentation of solid phases. The histogram (a) illustrates the approximate overlapping intensity distributions of three different phases. Boundaries are set at voxel intensities where overlap is a minimum, and all voxels with intensities between the boundaries are assumed to be of the particular phase. A 3D rendering of a grayscale volume is shown in (b), and the corresponding aggregates, cement hydrates, and unhydrated particles are shown in (c), (d), and (e) respectively.

Once all the separate objects have been identified, they can be measured and further scrutinized. Fast algorithms exist for both connected components identification and analysis [19]. Example object measurements include volume, surface area, centroid, and shape analysis. We should note that a connected components analysis as described above can be afoiled situation where large objects (e.g. two aggregate particles) touch over a very small region. In such a case, the analysis considers them to be part of the same object because of the connecting filament. These cases require the use of a more sophisticated algorithm, such as watershed segmentation, to separate the objects.

When connectivity of a particular phase is established, it opens the door to a wide range of issues. Examples include fluid flow through a porous medium, electrical conductivity, or progression of chemical reactions.

4.2. Micromechanical Measurements

An important aspect of X-ray CT analysis is that in most materials characterization cases it is nondestructive. The reason this is significant is that in materials research we are frequently interested in microstructural changes in the
material when it undergoes some type of loading or transformation. In the application presented here, X-ray microtomography was used to examine damage in small cement mortar specimens that were subjected to mechanical loading [20,21]. The goal of the work was to make quantitative relationships between external load, specimen deformation, and internal specimen damage. Towards this end, a small mechanical testing frame was constructed in such a way that tomographic scans could be made of the specimen while under load. Specimen load and deformation could be continually monitored during scan. The experimental protocol was as follows: a specimen was placed in the load frame, where a tomographic scan was done on the specimen in the undamaged state. A prescribed load was then applied, and the specimen was subjected to another tomographic scan. By repeating this process, we may examine the changes in internal structure that result from an increasing load. In the experiments detailed below, a uniaxial compression cylinder was used for fracture studies, but split cylinder compression and axial tension have been used in other studies.

The results of an example experiment are illustrated in Fig. 8, which shows two different slice views of a specimen subjected to progressively higher levels of deformation. Qualitatively we can observe not only the increasing amount of cracking in the specimen, but also the complexity and interconnectedness of the crack network. In the horizontal (circular) slices we see a crack form on the left side of the specimen, and in subsequent images the crack not only grows, but new and independent crack networks form. In the vertical slices it would seem there is only a single vertical crack until the damage is extensive in the bottom image. This is particularly important because it illustrates the three-dimensionality of the crack network. The crack network cannot be described or captured in a single 2D plane.

A connected component analysis can be applied to measure the properties of the crack network, including crack surface area, volume, and connectivity. Of interest in one study [22] was the energy of fracture for these materials. In that study, the net work of load was established from load-deformation information, while the incremental change in crack surface area was determined from an analysis of the tomographic images. The significance of the microtomographic images is that measurements of internal crack surfaces do not rely on simplifications such as planar cracks. The connected component-based measurement of surface area can include all the roughness and branching that exists in the real material.

Fig. 9 illustrates the complexity of the crack network. In each of Fig. 9a and b, the largest connected crack object is shown in a 3D rendering. Fig. 9a shows the early stage of cracking, where there is basically a single planer, albeit rough crack. In Fig. 9b, however the crack has grown, branched, and connected with other crack networks so that it appears as an undistinguishable complex object. The complexity can be characterized using a variety of geometric properties, such as surface area-to-volume ratio, average roughness, or fractal dimension [23,24]. These types of parameters have been linked to bulk mechanical properties, although in those studies, crack roughness was measured either by thin sectioning, or post fracture analysis. Using the tomographic data, the fractal dimension of the largest crack objects was calculated using a box-counting technique, where the number of voxels necessary to contain the feature is plotted against the size of the voxels. The slope of the resulting plot is the fractal dimension. In this fracture study the fractal dimension of the crack network was found to correlate very well with a scalar damage variable that is calculated based on the loss of specimen stiffness. While the relationship is strictly empirical, it could offer insight into the role of microstructural complexity in bulk material behavior.

Current applications of X-ray microtomography to micro-mechanics problems include measuring things such as particle contacts and localization phenomena in granular materials. In experiments such as the one described above, where multiple scans are made of the same specimen under different load states, 3D deformation fields can be determined using a variety of techniques such as digital image correlation or 3D image registration. Ultimately, we can only make kinematic measurements. In order to advance our knowledge in mechanics the tomographic measurements must be tied in with models that can relate forces to deformations. In one approach [25], discrete element lattice models are used to represent measured microstructural features. Such a model not only allows the inclusion of different phases, but a model specimen can be prepared in which there is a direct correspondence between the phase distributions in the model specimen with that of the real specimen.

4.3 Brief Sample of Other Applications

The rapid growth of this field, both in the range of commercially available instrumentation, and in the number of different fields finding use for the techniques makes a comprehensive review impractical for a tutorial presentation. A number of fine review articles are in print [26–28], and we attempt here to point the reader to a range of example applications.

Metals are often a challenge for X-ray CT applications due to the relatively high absorption absorption. However researchers have applied the technique to fracture [29,30] and fatigue crack propagation [31] of Al alloys, while others used the technique to examine coke processing parameters [32]. Researchers studying powders, foams, and other porous materials of various types have exploited the three-dimensionality of the technique for shape characterization of particles [33–35] and pore space [36–38]. In composite materials, applications of X-ray CT include characterization of fibers [39,40], pore geometry [41], and damage [42]. Not surprisingly, applications extend to materials with biological fibers [43], including paper [44] and wood [45].

Fig. 8 – Illustration of progressive fracture of a mortar cylinder loaded in compression, captured at various damage levels by X-ray microtomography. (a) shows the orientation planes, while the paired horizontal and vertical slices show the undamaged specimen (b) and the same specimen at three progressively higher levels of damage (c)–(e).
Fig. 9 – Three-dimensional renderings of crack surfaces in a fractured cement-based composite. (a) shows the main splitting crack of the initial fracture, while (b) shows the same crack surface, after additional loading. The crack network has so many branches and interconnections that it is difficult to discern any order in the crack system.
5. Summary and Conclusions

The lesson of this tutorial paper is that X-ray microtomography can play an important part in the solution of many materials characterization problems. The advantages may be summarized as follows:

- Internal material features can be imaged in three dimensions at relatively high spatial resolution.
- The technique is nondestructive for most practical materials problems.
- Quantitative measurements can be made from the resulting digital image data, including the spatial distribution and volume fraction of phases, as well as the changes in phases due to a range of mechanical or chemical phenomena.

Unfortunately, currently no materials characterization technique is without its limitations. For X-ray microtomography, limitations include the penetrating ability of the X-rays relative to the density of the material sample. Dense metals, for example, require either very high-energy X-rays, or very small specimens. Similarly, the method suffers when the material phases have large differences in X-ray absorption. In such a case, the resulting images will have very poor contrast within the less absorptive phases. Finally, in the case of synchrotron X-ray sources, access is limited by the availability of facilities.

For the future, we see a continued increase in applications as evidenced by the numerous conferences and publications dedicated to X-ray CT (e.g. 46–51). While physics places some limits on what we can do with X-rays, the amount of useful information we can extract from CT scans continues to grow thanks to ever expanding computing power, along with improvements in image acquisition capabilities. In all likelihood we will see the most growth in conventional source, laboratory scale instruments. There are a number of vendors producing turnkey systems that boast continually higher flux and energy, and improvements in conventional X-ray sources are pushing spatial resolution well into the sub-micrometer range for some systems. Adding to the lure of some of these systems are the add-on packages available, such as temperature control and in situ loading devices.

While the convenience of in-house laboratory systems will likely fuel growth in usage, there will always be a role for the unique characteristics of synchrotron radiation. For example, when the high flux X-ray beam is combined with a high-speed detector and fast reconstruction algorithms, 3D images can be produced at a speed that begins to approach real time. The ability to have a very monochromatic beam at a synchrotron also allows for energy difference X-ray microtomography, in which images from two or more energies are used to increase sensitivity to different elements in the sample. This technique utilizes the strong variation in X-ray absorption as the X-ray energy is varied in the vicinity of an elemental absorption edge [52].

Finally, advances in visualization 3D rendering are allowing users to extract ever more qualitative as well as quantitative information from the tomographic data. A wide range of both commercial and open source software is available for this purpose. Animations illustrating evolutionary processes can assist in evaluation of mechanisms in a way that 2D analyses cannot. While 3D rendering is a computationally intensive process, parallelizing code for multi-core processors and graphics processing units make it a tractable problem for nearly all scientists and engineers.

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