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E. Anne Sivers

Energy Technology Division
ARGONNE NATIONAL LABORATORY
Argonne, IL 60439

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USE OF MULTIPLE CT SCANS TO ACCOMMODATE LARGE OBJECTS AND STRETCH DYNAMIC RANGE OF DETECTABILITY*

E. A. Sivers**

Argonne National Laboratory, Argonne, IL***

Rotate-only X-ray CT scanners are preferred for their speed and dose utilization, but suffer from the restriction that the scanned object must fit within the radiation beam. In addition, the ratio of signals unattenuated by air paths to those penetrating thick, dense objects often exceeds the dynamic range of conventional X-ray detectors. Both of these disadvantages can be removed for objects larger than the X-ray beam by taking multiple scans, each of which exposes only part of the object. These partial data sets can then be merged to produce a complete data set. For most objects, it is also possible to separately expose regions in which the ratios between the extremes of attenuation are much lower than that between air and the maximum path length. It is therefore possible to use a higher flux to image denser regions, improving signal-to-noise ratios and yielding images superior to those of larger scanners having the same dynamic range.

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*** Current address; 18028 Westminster Dr., Lake Oswego, OR 97034

1. Introduction

Two of the most formidable obstructions in the application of 3D X-Ray CT (3D-XRCT) to industrial inspection are the small size of the best area detectors¹ and the limited dynamic range of their data collection systems. However, if multiple scans from a small detector can be combined seamlessly into a large image, often the dynamic range can be expanded by maximizing the flux to separate regions in which the range of thicknesses is fairly small. Moving a small detector to accommodate a large object is not new, but early systems were slow and mechanically complicated. The optimum 3D-XRCT industrial system today usually involves only a stationary X-ray source and area detector with a turntable on which to rotate the object being scanned. In addition, the turntable is usually mounted on two or three translational stages to position the object. However, the object must fit within the width of the "cone" formed by the X-ray source and the detector.

There are several possible options that will permit such a system to scan an object wider than the X-ray cone beam. The most obvious is simply to translate the detector horizontally within its plane. However, the flux output from a conventional X-ray source is not isotropic and this will usually require movement of the source; either translation, or rotation of the source about its vertical axis. It is simpler to rigidly rotate both the detector and the source around the vertical axis of the source, but this requires a substantial mechanical stage. An equivalent choice is to keep the source and detector stationary and rotate the turntable axis about the vertical axis of the X-ray source, but this option still requires an additional rotational stage. It will be shown that it is also equivalent to simply translate the turntable in two orthogonal movements, such that the radial distance from the

turntable axis to the X-ray source remains constant, followed by a rotation of the turntable about its own axis. This option requires no additional hardware or system calibration and can be used to increase the width of the X-ray cone beam by as much as an order of magnitude.

2. Experimental design/data acquisition

The X-Y plane of the experimental system² used to acquire multiple scans for the implementation of cone-beam expansion ("multiscan") is shown in Fig 1. The source is a 150 kVp microfocus X-ray tube and the detector is a 9-inch image intensifier. The turntable is mounted on a translation stage that moves parallel to the Y axis, which is itself mounted on a translation stage that moves parallel to the X axis. For an object smaller than the X-ray/detector cone beam, 3D-XRCT data is collected by centering the object on the turntable and rotating it through 360°. Multiscan data acquisition is similar except that the turntable is repositioned between 360° revolutions such that the radial distance from the turntable axis to the X-ray source remains constant, as shown in Fig 2. This sketch of the X-Y plane shows the turntable in two multiscan positions as well as the equivalent, hypothetical position of a rotated "virtual" detector. As is shown in the Appendix, it is necessary to increment the angle of the translated turntable by an amount $\Delta\theta = \tan^{-1} (-\Delta y/STO)$, where Δy is the Y increment from the central position and STO is the perpendicular distance between the turntable axis and the X-ray source, to obtain a position equivalent to rotation in the X-Y plane of the turntable about the X-ray source. In addition, it is apparent from Fig 2 that the sample spacing must be adjusted in off-centered multiscans to account for the projection of the "virtual" detector sampling upon the Y-Z plane. It is shown in the Appendix that desired

samples at (y,z) on the Y-Z plane can be interpolated from samples (y",z") in off-centered multiscans by the formulas

$$y'' = \frac{STD (STD \sin\Delta\theta + y \cos\Delta\theta)}{(STD \cos\Delta\theta - y \sin\Delta\theta)} \quad (1)$$

$$z'' = \frac{(STD z)}{(STD \cos\Delta\theta - y \sin\Delta\theta)} \quad (2)$$

where STD is the perpendicular distance between the detector and the X-ray source.

Signal-to-noise ratios are maximized in multiscans by adjusting X-ray output flux and/or data collection times to full scale for each separate scan. Flux calibration between adjacent scans is effected by comparing values in overlapping regions. It is also necessary to measure scanner parameters accurately. Successful data combination depends strongly on the accuracy of the parameter STD. If STD cannot be measured accurately, it is necessary to measure the resulting sample misalignment in overlapping regions and correct for it before data combination.

3. Experimental Results

An example of the reconstruction of a large object imaged with multiscan data acquisition is shown in Fig 3. The object is a right circular annulus with an outer diameter of 21.0 cm and a wall thickness of about 0.3 cm. It is composed of laminated sheets of unsintered Al_2O_3 and is susceptible to delaminations, inclusions, and voids . The sections shown in Fig 3 are taken from the plane that contains the X-ray source and is perpendicular to the area detector. The turntable was about 51. cm from the X-ray source and the width of

the cone beam there was about 7. cm. To allow for overlaps and air readings, five separate scans were used to construct the composite data file and data acquisition time was adjusted to maximize the X-ray flux through each section of the object. The sample pitch in the individual scans is 0.007 cm but the sample pitch in the composite scan has been averaged to 0.035 cm to reduce the data processing load.

Each of the three segments of the right circular annulus shown in Fig 3 covers about 45°. The first segment is relatively homogeneous and uniform. However, the second segment shows a clear delamination, and the third exhibits both voids and inclusions. The sampling in these images is such that the wall thickness spans about 8 samples ("pixels"). The sample spacing can be reduced by averaging fewer of the original samples, but it is adequate to determine the flaws in this object and processing time increases as the square of the number of samples.

4. Conclusion

The advent of superior area detectors with inherent size limitations has motivated the use of multiscan techniques to perform 3D-XRCT on large objects. An added benefit is the ability stretch the dynamic range of the detector by tailoring the X-ray flux to the attenuation range in each separate scan. By carefully calibrating the imaging system, it is possible to produce artifact-free images that have a higher signal-to-noise ratio than images made by a single large detector having the same dynamic range.

Appendix

To derive Eqns 1 and 2, consider the two coordinate systems illustrated in Fig 2: the laboratory (L) coordinate system is centered on the X-ray source; and the detector (D) coordinate system is centered on the detector with the positive X^D axis perpendicular to the detector, and the positive Y^D axis parallel to the detector. In each case, the corresponding Z axis is perpendicular to, and projects out of, the page and the origin is in the plane of the X-ray source. A point on the detector has the coordinates P^L in the laboratory system and P^D in the detector system. When the X axes of the two systems coincide, the coordinates of the point are related by

$$P^L = P^D - STD X^L \quad (A-1)$$

where STD is the distance between the coordinate origins and X^L is the unit vector in the X direction. If the detector is rotated rigidly about the Z^L axis by the rotation operator

$$R_z^{\Delta\theta} = \begin{pmatrix} \cos\Delta\theta & -\sin\Delta\theta & 0 \\ \sin\Delta\theta & \cos\Delta\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (A-2)$$

a point on the detector has new coordinates P_R^L in the laboratory system.

$$P_R^L = R_z^{\Delta\theta} (P^D - STD X^L) \quad (A-3)$$

Eqn A-3 can also be inverted to express the coordinates of a point in the laboratory system in the coordinates of the rotated detector system.

$$P^D = (R_z^{\Delta\theta})^{-1} P_R^L + STD X^L \quad (A-4)$$

An X-ray in the laboratory system can be expressed as the line L drawn between the origin O and a point on the virtual detector V , where

$$O = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, \quad V = \begin{pmatrix} -STD \\ y \\ z \end{pmatrix}, \quad L = \begin{pmatrix} \tau \cos \alpha \\ \tau \cos \beta \\ \tau \cos \gamma \end{pmatrix} \quad (\text{A-5})$$

In Eqn A-5, τ is a distance scalar and $\cos \alpha$, $\cos \beta$, and $\cos \gamma$ are the direction cosines of the line in the X^L , Y^L , and Z^L directions respectively. If L is substituted for P_R^L in Eqn A-4, the point P^D in the rotated detector coordinated system that is intersected by the X-ray,

$$P^D = \begin{pmatrix} 0 \\ y'' \\ z'' \end{pmatrix} \quad (\text{A-6})$$

is expressed in terms of the coordinates of the point on the virtual detector. Solving for τ and substituting into the expressions for y'' and z'' gives Eqns 1 and 2.

Examination of Fig 2 shows that rotating the detector by $-\Delta\theta$ about the Z^L axis while the turntable remains stationary is operationally equivalent to rotating the turntable by $\Delta\theta$ about the Z^L axis while the detector remains stationary. It remains to demonstrate that this rotation of the turntable about the X-ray source is equivalent to two translations in the laboratory coordinate system plus a rotation of the turntable about its own Z axis. Consider a third coordinate system centered on the turntable (T) with its origin in the plane of the X-ray source. When the X^T axis of the turntable coincides with the X^L axis of the laboratory system, a point P^T on the turntable has coordinates P^L in the laboratory system.

$$P^L = P^T - STO X^L \quad (\text{A-7})$$

where STO is the distance between the X-ray source and the turntable axis. If the turntable

is rotated rigidly about the Z^L axis by the rotation operator $R_z^{\Delta\theta}$ defined in Eqn A-2, the coordinates of the rotated point P_R^L are given by

$$P_R^L = R_z^{\Delta\theta} P^T - STO \cos\Delta\theta X^L - STO \sin\Delta\theta Y^L \quad (A-8)$$

The difference between Eqns A-8 and A-7 is

$$(R_z^{\Delta\theta} - I)P^L = (R_z^{\Delta\theta} - I)P^T + STO(1 - \cos\Delta\theta) X^L - STO \sin\Delta\theta Y^L \quad (A-9)$$

Thus, the rotation of the turntable about the laboratory Z^L axis is equivalent to a rotation of the turntable about its own Z^T axis followed by two orthogonal translations in the laboratory system.

Figure Captions

Fig 1 A sketch of the experimental system used to acquire 3D-XRCT multiscan images.

Fig 2 A sketch of the geometry of the 3D-XRCT data acquisition system.

Fig 3 Three 45° segments of a right circular annulus reconstructed from five separate multiscans.

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