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High-Speed X-ray Computed Tomography

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43.1 Introduction

Across a range of applications, there has been a steady trend toward tomographic imaging at ever shorter time-scales. In medical imaging, the main driver for high-speed CT has been cardiac imaging, with the aim of producing tomographic images of a beating heart (Harlock et al. 2009). In industrial process monitoring, a key goal has been in situ imaging of flow in pipes, with the specific problem of three phase (oil, gas, water) flows in the petroleum industry being of special interest (see also Section III, Chapter 32). The development of laboratory systems has been motivated by applications in experimental fluid dynamics, such as the study of fluid and granular flow and mixing, in materials science, such as the study of dynamic processes including the development of cracks and changes in the microstructure of materials due to heating and cooling (Maire and Withers 2014), and in oil and gas exploration, such as imaging flow through porous media. As imaging systems have become faster, this has enabled development of new experimental techniques; it has also created significant challenges, both for the design and engineering of the CT system hardware, and also mathematical and computational challenges for reconstruction of the resulting tomographic images.

As a secondary driver toward faster scanning, there is also the need across a range of applications to perform three-dimensional scans of static objects as quickly as possible. In the manufacturing industry, this includes applications in production line process monitoring, non-destructive testing, and quality assurance.

In aviation security, it is desirable to scan luggage in three dimensions in order to better identify potential threat objects than is possible with simple two-dimensional projection X-rays. In both cases, the primary motivation has been to improve efficiency and reduce cost by scanning faster.

43.2 Fast CT Technology

In this section, we give an overview of the technologies used for high-speed tomographic imaging. Development of high-speed CT began with conventional systems, as used in medical, industrial, and laboratory imaging. Such systems were not originally designed for fast scanning, and are limited in their achievable speed by moving parts. To get past this limit, it has been necessary to develop technology to eliminate the moving parts from the system; three approaches to address this problem are discussed.

43.2.1 Conventional Medical CT Systems

Conventional medical X-ray tomography systems for three-dimensional imaging use a single X-ray source that rotates on a gantry opposite an array of detectors. The detector array consists of multiple rows of detectors arranged in a circular arc. The patient is translated in the direction of the rotation axis, so with respect to the patient, the source travels on a helical trajectory (helical scan cone beam, Kalender 2005) (see also Section III, Chapter 32).
As medical CT systems evolved in the seventies, so-called “fourth generation” scanners were also developed, in which only one source rotates inside a complete ring of detectors (Kalender 2005). However, the “third generation” conventional scanners quickly became the dominant platform, and it is not clear whether this would have resulted in faster scanning. Additionally, during the eighties, a system utilizing multiple sources and detectors was developed by the Mayo Clinic. Known as the Dynamic Spatial Reconstructor (DSR), this system paired an array of 14 X-ray sources with 14 detector screens and cameras on a rotating gantry, and was theoretically capable of imaging at 60 frames per second (Robb et al. 1983). However, the high cost and complexity of this system meant that only a single example was ever built.

Further development of non-standard medical CT architectures continues as a niche area of research; for example, Besson (2014) proposes a system involving concentric, independently rotating rings of sources and detectors.

### 43.2.3 Laboratory CT Systems

In non-destructive testing and laboratory CT, typical systems comprise a fixed source and a detector in a vertical plane that is either fixed or can be set at a fixed distance from the source. This is either a flat-panel rectangular detector or a system involving a flat scintillator and an optical camera providing a range of zoom levels. The sample is supported on a stage that can rotate and translate, and in typical use, once it is correctly positioned it is simply rotated about a vertical axis (circular scan cone beam) or translated vertically as it rotates (helical scan cone beam).

As with medical systems, conventional laboratory X-ray CT systems are also limited in speed by the physical motion of the sample, but are additionally constrained by the photon flux of the source. This is a particular problem for the highest resolution micro-CT systems, where the small focal spot size required for the highest spatial resolution necessitates low source power. To this end, there has been progress toward sources with higher brightness, based on liquid metal jet technology (Zabler et al. 2012). This offers the potential for an order of magnitude improvement in brightness, and therefore, in scanning speed, compared to conventional laboratory sources; however, this is still insufficient for high-speed dynamic tomography at sub-second time-scales.

#### 43.2.4 High-Speed Synchrotron Imaging

Tomographic imaging using synchrotron sources has been used extensively for high-speed dynamic experiments in materials science and other disciplines (see also Section I, Chapter 8). This has enabled novel dynamic experiments at very short time-scales, but achievable scanning speed is still somewhat limited by the need to physically rotate the sample in the path of the beam (Mokso et al. 2011). The rotation also causes compromises for experimental design; for example, the forces induced by rotation of the sample would not permit observation of a moving fluid flow without altering the process being observed.

Another motivating factor for the development of high-speed laboratory-based systems for dynamic experiments is the long wait times and competition for beam time at synchrotrons. To address this problem, the Compact Light Source from Lyncan Technologies has been developed (Bech et al. 2009). This promises to bring synchrotron imaging capabilities, including potential for high-speed dynamic tomography, to smaller scale facilities.

#### 43.2.5 Systems with Multiple Simultaneously Operating Source

Essentially, three fundamental approaches have emerged to solve the problem of building a fast CT scanner with no moving parts; the first of these is to use multiple static sources simultaneously. A pioneering example is from the Bergen group (Johansen et al. 1996, Maad et al. 2010), who developed a system using five stationary Am-241 gamma ray sources, each opposite a block of 17 detector elements (Figure 43.1). This images a single plane at up to 100 frames per second, but with only five projections has limited spatial resolution. Nevertheless, it proved effective for in situ imaging of multi-phase flow in pipes. A similar acquisition scheme is described theoretically, from the point of view of reconstruction algorithms, in Niemi et al. (2015).

For fast three-dimensional scanning of baggage in aviation security, several systems employing multiple, continuously operating sources exist. Examples include the L-3 MV3D (Poland 2012), which uses a handful of sources (though the exact number is not given) positioned around the baggage tunnel, and multiple detectors arranged in a skewed geometry to obtain projections from an increased range of angles as objects pass through the scanner. The ScanTech SENTINEL III (Champley et al. 2016) employs...
four sources paired with four linear arrays of dual-energy detectors, to measure projections in four separate planes through the object. Similar systems from other manufacturers exist, though technical details are not available.

### 43.2.6 Swept Electron Beam CT Systems

The second approach to development of a CT system with no moving parts is to arrange for one or more electron guns to sweep across different targets, producing what is effectively an electronically moveable source with no mechanically moving components. In fast medical CT, a technique known as electron beam tomography (EBT) uses a swept electron beam over a tungsten target, in a 210 degree arc of a circle, to produce a fast two-dimensional cross sectional image (Figure 43.2). Originally introduced by Haimson (1979), and subsequently developed by Boyd and Imatron Inc. (Boyd and Lipton 1983, Boyd et al. 1987), medical EBT systems are commercially available, although not in widespread use. Such systems have frame rates up to 30 fps (Hill 2005) and are able to image multiple slices using multiple target rings. There is evidence that the Imatron scanners have been investigated for use in security applications; see, for example, Vargas and La Riviere (2014).

The Dresden group (Hampel et al. 2005, Fischer et al. 2008) developed a system similar to EBT for fast imaging of flows in the laboratory (Figure 43.3). Like medical EBT systems, it scans
the electron beam over a target with an arc of around 280 degrees. The system is designed to image a single planar cross-section of the contents of a pipe but the detector array is a circular arrangement of 240 cadmium zinc telluride (CZT) detectors of diameter 135 mm, offset from the target by 5 mm. It therefore produces only an approximate fan-beam scan of the cross-section, but can do so at 1000 frames per second. The group’s more recent work (Stürzel et al. 2011, Zhang et al. 2013) reports frame rates up to 8000 per second.

43.2.7 Switched-Source CT Systems

The third approach is to use multiple, static sources combined with multiple detectors and sequentially switch the sources electronically. Hori et al. (1996) and Misawa et al. (2003) developed systems with multiple X-ray tubes which are switched sequentially. A more advanced example of such a system was also developed by Rapiscan Systems, known as Real-Time Tomography (RTT) (Morton et al. 1999, 2010), and comprises an approximately circular array of X-ray sources with a corresponding approximately cylindrical array of X-ray detectors. As in the Dresden EBT system, the plane containing the X-ray sources is offset from the outer plane of X-ray detectors to avoid the primary beam irradiating the back of the detector array. The X-ray sources comprise an array of electron guns, each independently controlled by an electronic switching circuit that can be pulsed in microsecond time-scales. As in other systems, the electron beam from a source is accelerated through a high potential difference and strikes a tungsten-coated anode to produce X-rays. This single anode is arranged in a circular pattern such that each electron gun irradiates a different region of the anode, resulting in an effective X-ray focus when viewed from the detectors, with a typical spot size of around 1 mm. The control electronics are programmable providing flexibility in the excitation pattern. Frame rates of up to 480 per second are possible with current technology.

The original RTT system, known as RTT20, has a 20 cm bore, an incomplete ring of sources, and a complete single ring of detectors, and was designed originally for imaging flows in pipes (Thompson et al. 2015). The geometry is shown in Figure 43.4. As the need for fast baggage security screening systems was apparent, this was developed into a prototype baggage scanning system with the addition of a conveyor belt. Subsequent production baggage screening systems were developed, known as the RTT80 and RTT110 (Figure 43.5), with 80 and 110 cm diameter bores respectively (Figure 43.5). These systems have a complete polygonal-cylinder of multi-row detectors and are capable of fast three-dimensional scanning of baggage travelling on a conveyor belt at 0.5 m/s. The RTT110 systems are now widely deployed in airports worldwide and a system is installed in the Henry Moseley X-ray Imaging facility at the University of Manchester for experimental scientific and engineering applications (Warnett et al. 2016).

FIGURE 43.4 The RTT20 geometry, showing locations of the sources, detectors, and scanned region (left: y–z cross-section with exaggerated z scale to show offset between source and detector planes; right: x–y cross-section).
Reconstruction Algorithms for Fast Dynamic CT

43.3 Analytical Algorithms

To acquire dynamic data, a CT system is generally operated continuously, with the cycle of data acquisition repeated so that each complete set of projections is considered as a time frame. For high-speed CT systems such as EBT or switched-source systems, the imaged region is typically a two-dimensional slice, or small set of slices, so for reconstruction of single time frames, this amounts to simple inversion of the two-dimensional fan-beam Radon transform. Analytical algorithms for this inversion are well-known (Kak and Slaney 1988) (see also Section III, Chapter 33).

Analytical reconstruction of independent time frames works well when the change in the object is relatively slow compared with the frame rate, but as in all fast tomography systems, some new ideas are needed when the system being observed is changing on a similar time scale to the frame rate. In such cases, the data from each projection of the frame will be the Radon transform of a different function (image). Typically, the data will be inconsistent (not in the range of the Radon transform). Different reconstruction algorithms will behave differently with inconsistent data but the result will be what is typically observed as a motion artifact, and not what we might hope for, such as a time average image.

Traditional fan-beam geometry reconstruction involves analytical algorithms in the family of filtered back projection (FBP) methods. These methods typically involve the application of a one-dimensional spatial filter to each projection combined at each image pixel by back projection, that is, application of the adjoint Radon transform. The advantage of such methods is that they can be implemented to run very efficiently, easily capable of delivering real time reconstruction on modern computer hardware. A limitation of such methods for static tomography problems is that they work best with uniformly sampled data in the projection and detector coordinates, as this allows filters to be applied efficiently using fast Fourier transforms. Indeed, practically, they tend to require more data than is theoretically required for a given resolution. Their behavior on inconsistent data is not well understood but is observed to be poor, and when we have missing data, it is difficult to incorporate a priori assumptions about the image to compensate for that.

43.3.2 Dynamic Reconstruction Using Spatio-Temporal Regularization

In contrast to the analytical reconstruction algorithms, matrix based (algebraic iterative) and optimization based (statistical iterative) methods involve a discrete sampling approach, without the underlying assumption of a continuum of data inherent in analytic reconstruction methods (see also Section III, Chapter 34). The basic approach is to define the image (later the time series of images) to be a vector $x$ of pixel or voxel values and the data corresponding to each source–detector pair we measure as vector $b$. We then define a matrix $A$ which encodes the intersection of the beam of X-rays between the source and detector with the image pixel or voxel. Simplistically, we wish to solve the linear system $Ax = b$. This will typically be a large, sparse linear system and so iterative rather than direct methods of numerical linear algebra are used.

One approach that has evolved in CT is to use a slowly converging but simple iterative scheme, such as the Landweber or Kaczmarz method, and terminate the iteration sequence before (semi-)convergence. As expected, in most inverse problems, the linear system is ill conditioned (Hansen 2007) and so, if the system is solved exactly, the solution will vary dramatically with errors in the data. Moreover, when the number of degrees of freedom in the image is smaller than the number of measurements, the system will be inconsistent in the presence of measurement and modeling errors. The Kaczmarz algorithm, which was reinvented as Algebraic Reconstruction Technique (ART) in CT, does not converge for an over determined system (inconsistent). Other methods such as Landweber’s method or conjugate
gradient least squares (CGLS) converge to the least squares solution, but will still only be semi-convergent for ill conditioned systems (so the iteration eventually diverges). Even for static problems, the traditional approach of terminating the iteration sequence using some fixed criterion has the difficulty that the solution obtained is dependent on the algorithm used, and it is not clear what *a priori* assumptions about the image would lead to that solution.

A standard approach to overcome ill conditioning in inverse problems is to replace the least squares approach of minimizing

\[ \|Ax - b\|^2 \]  \hspace{1cm} (43.1)

by instead minimizing

\[ \|Ax - b\|^2 + \alpha^2 \|Lx\|^2 \]  \hspace{1cm} (43.2)

where \(L\) is the identity matrix or a matrix encoding a difference operator on neighboring pixels and \(\alpha\) is a regularization factor which determines the trade-off between fitting the data and over fitting the data due to errors and instability. Using a finite difference matrix for \(L\) encodes the constraint that in a reasonable solution the gray values of neighboring pixels (or voxels in 3D) would not differ by too much. Given an algorithm that gives the least squares solution efficiently for large sparse systems such as CGLS, we can apply the same algorithm to the augmented system

\[
\begin{bmatrix}
A \\
\alpha L
\end{bmatrix} x =
\begin{bmatrix}
b \\
0
\end{bmatrix},
\]  \hspace{1cm} (43.3)

and the least squares solution is the minimizer of Equation 43.2. We now extend this idea to time series of images. Take \(x\) now to be the vector of time series of images, each successive block being an image frame. Similarly, \(b\) will be the time series of data, each block being a frame of data. If the measurements were acquired with sufficient speed that each frame could be considered instantaneous, we would have nothing to do, but instead, we have to consider that each projection of the frame was taken at a different instant. A sophisticated approach to this that produces the optimal image at each stage with the data available, as well as updating the temporal correlations, would be to do Kalman filtering as Vauhkonen et al. (1998) did for impedance tomography.

A simpler approach, feasible for small datasets as given by switched source systems such as the Rapiscan RTT20 (Thompson

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**FIGURE 43.6** Reconstructed images of a single frame from the oil and water data. Figures (a), (c), (e) used 245 projections while (b), (d), (f) used 49 projections. (a and b) standard filtered back projection, (c and d) not temporal regularization, (e and f) with temporal regularization.
et al. 2012a), with relatively short runs of data, is to solve the larger system where the new $A$ matrix is the block diagonal matrix which is the Kronecker product of the $p$ by $p$ identity matrix $I \otimes A$, where $p$ is the number of frames. We then construct the new regularization matrix to encode not just correlations between nearby pixels but also subsequent values of the same pixel, with different regularization parameters for space and time (see Thompson 2015). Using a dataset collected with the conventional firing order of a vessel containing oil, water, and air sloshing as it moved backwards and forwards on the conveyor belt, the authors were able to show (Thompson 2015) that, with this space–time regularization, it is possible to cut the number of projections required dramatically and still resolve the oil, water, and air interfaces in the animated time series of images. Results shown in Figure 43.6 show the effect of the temporal regularization coefficient when the number of projections is cut from 245 to 49, while missing data artifacts appear without it.

### 43.3.3 Fast Three-Dimensional Scanning

Flow visualization and analysis, and numerous other dynamic imaging problems, require at least some three-dimensional capability. If a flow is approximately translationally invariant, a time series of two-dimensional cross-sections is useful and informative, but in more complex flows, this is not the case. A possibility would be the extension of electron beam systems to a full circular scan with multi-row detectors. However, a single static electron gun cannot scan a full circular target, so more than one is needed. Such a design would also allow for a helical scan geometry if the sample or the apparatus were translated parallel to the rotation axis. It would still however suffer from the limitation that the detector array needs to be offset axially from the X-ray sources.

Switched source systems, such as the larger Rapiscan RTT systems, may more easily be equipped with several detector rings, allowing the possibility of dynamic scanning of multiple slices. Fast three-dimensional volumetric scanning of static objects, such as baggage in security applications, is achieved by translating the object through the scanner on a conveyor belt. Effectively, the temporal dimension is traded for volumetric ($z$) information in this mode of operation. Although the offset source–detector geometry results in incomplete sampling of the Fourier space, the multiple detector rings allow a sufficient amount of data to be collected for three-dimensional volumes to be reconstructed with only minor artifact levels.

### 43.3.4 Firing Order and Sampling in Fast Tomography Systems

Switched source and electron beam systems free us from the necessity to fire our sources sequentially, as we would in a conventional system if we were to acquire a frame quickly. With a switched source system, it is natural to think of a complete set of projections as equivalent to a full revolution of a moving source system, but sources may be fired in almost any order we choose, subject to limits on the temperature and heat dissipation of the target anode. This effectively gives us almost complete freedom to choose our next firing, and in future systems, we expect that the sequence might be computed adaptively on the fly in the light of the reconstructed image so far using ideas from optimal design of experiments in statistics. A more modest goal is to find a fixed firing sequence that gives the best time series of reconstructed images in typical situations (Thompson et al. 2012b).

For a general switched source system with $N$ sources, we define a firing order as a function $\Phi$ from and to the set of integers $1, \ldots, N$ so that at the $i$th step of the firing cycle source $\Phi(i)$ fires. To use all sources within a cycle, this function would be a bijection. Sequential firing is, as expected, a bad choice—intuitively, we need projections from as diverse as possible a set of angles before the sample changes too much, so we clearly need a spread of angles.

In neutron tomography of dynamic processes, where the choice of projection angle is effectively continuous, Kaestner et al., using theoretical results by Kohler (2004), choose successive projections based on the golden ratio using $i\pi(1 + \sqrt{5})/2 \mod \pi$ radians as the $i$th projection angle. Thompson et al. (2012c, 2015) showed that the closest approximation to this available within the geometry of a switched source system, the optimal firing order combined with spatio-temporal regularization, resulted in improved dynamic images for the same number of projections. For three-dimensional volumetric reconstruction of static objects in a multi-row system such as the Rapiscan RTT80, there is also a need for an optimal firing order. Following the development of multiple head rotating gantry systems, it is natural to consider multi-threaded helices. For example, if there were $4N$ sources, we might adopt a firing sequence $1, N+1, 2N+1, 3N+1, 2, N+2, \ldots$ corresponding to approximately a four-threaded helical trajectory for a sample that was translated parallel to the rotation axis. There are explicit analytic reconstruction algorithms for multi-threaded helices; however, these are not applicable in the case of a system with offset source–detector geometry such as the RTT80.

If we are to use general algebraic reconstruction methods, we have complete freedom in our firing order, and experience with the two-dimensional case suggests that there might be an optimal number of helical threads or that a non-helical source firing order might be appropriate.

Thompson (2011) showed that, for switched source systems, the continuum notion of a firing order was no longer relevant. Instead, he considered source firings as points on a cylinder corresponding to the source angle and the translation of the object (in the case of the RTT along the conveyor belt). He reasoned that the optimal source firing order was one that gave the most uniform sampling of points on that cylinder, as close as possible to a regular hexagonal lattice. An alternative criterion for optimality was to make the coverage of ray directions in each pixel as uniform as possible, and that gave rise to the same firing sequence, see Figure 43.7.

Lattice sampling methods have since been extended to single source systems (Thompson 2011, 2016) to make best use of the X-ray dose in a given time.

For systems in which a helical trajectory is used, explicit reconstruction methods such as Katsevich have been used for relatively fast reconstruction of data from rock core samples (Katsevich et al. 2015), and extension to multi-threaded helices is possible (Zhao et al. 2009). For offset cone beam systems with truncated data, rapid reconstruction can be performed using multi-sheet surface rebinning (Betcke and Lionheart 2013a,b).
boundaries than is afforded by a voxel image is attractive. Niemi (2015) have pioneered this for fast tomography.

### 43.4 Conclusions

Developments of fast CT systems are likely to continue along these lines with a highly flexible source firing sequence. Increasingly fast iterative computational methods will permit reconstruction of high-resolution time series of data. As the needs of users, especially in in situ process monitoring and non-destructive testing in industry, and in the study of dynamic processes in laboratory research progress systems become more clearly understood data collection strategies and reconstruction algorithms will become more closely adapted to their needs. We expect increasingly statistical methods will be used in design of firing patterns, in dynamic reconstruction of time series of images, and in uncertainty quantification in the parameters of the system under investigation.

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