TANGENTIAL CT, A COMPUTED TOMOGRAPHY METHOD DEVELOPED FOR INDUSTRIAL INSPECTION

Nand K. Gupta[1], Simon H.C. Hughes[1]& Bruce Isaacson[1]
Omega International Technology, Inc.

Abstract: During the past 25 years, Industrial X-Ray Computed Tomography (CT) has successfully evolved from the medical technology base. Today, two of the data collection methods derived from medical CT technology base have become popular for Industrial CT applications. The major industrial CT design methods are based on second generation and third generation medical CT data collection. At present, most noteworthy CT applications are in R&D and use second generation systems. The R&D applications require object size flexibility as wide range of object sizes are scanned, but generally scan speed is not an important issue. Third generation is generally used in applications that require inspection of many pieces because it is a faster data collection method. But, in most cases third generation is limited to a specific object or a small range of object sizes. These CT systems have been adapted from medical methods because they could take advantage of the extensive research and development efforts of the medical community but this development was based on the needs of the medical application. A new Tangential CT (TCT) volume data collection method has been developed with the industrial application in mind. It offers the advantage of object size flexibility inherent in second generation and increased speed similar to third generation data collection. TCT accumulates volume data through continuous and simultaneous multiple rotations and a single translation of the object through the x-ray beam formed by the x-ray source and detector array. The TCT system offers the object flexibility of second generation and high speed of third generation.

Introduction: Most of today's Industrial CT Scanners are based on the designs developed for medical CT system. Thus these designs often reflect medical requirements that are not necessarily efficient for industrial applications. Five generations of data collection methods have been developed for medical CT scanners[1]. These developments have resulted in faster and faster data collection but with more and more constraints dictated by the human object scanned. These constraints reduce the flexibility of the system and make it object specific. Recently a new technique has been developed which is a unique Volume CT data collection technique (Tangential CT Scanning) that is most suitable for industrial objects. The Tangential CT (TCT) scanning is a design specifically developed for industrial applications from ground up that utilizes the unique capabilities possible with industrial objects only. The TCT design uses the technical strength of the medical CT system while it avoids the extra constraints that are essential when dealing with live and sick patients.

Like the medical CT Systems, the TCT System uses a linear array of solid state detectors. Generally, solid state linear detector system offers significantly better (>16 bits) dynamic range compared to any type of Area Detector Systems like Image Intensifier Tubes, Amorphous Plates, Phosphor Screens / video cameras, etc. Most of these Area type Detector System exhibit << 12 Bit dynamic range due to higher electronic noise and more importantly due to x-ray noise from scatter signal. The linear detector arrays offer lower electronic noise and they can also be collimated against most of the x-ray scatter signal, thus offering significantly better performance.

For industrial applications, newer Volume CT scanners Systems use third generation data collection method, the full Cone X-Ray Beam coupled to some type of Area Detector System. While this is a fast data collection technique due to the use of the full Cone X-Ray Beam, there is no way to implement a scatter reducing collimator with any Area detector System. With a linear detector array, a slit collimator is easily implemented in front of the detector system to reduce the x-ray scatter signal thus further improving the signal quality. Also the third generation data collection method has optimum resolution for a limited range of part size. Industrial parts come in a wide variety of sizes and part size flexibility is important.

Presently, most Industrial scanners are not Cone Beam Volume CT machines but are single slice oriented scanners using an x-ray fan beam coupled to a linear detector array. Most of the single slice Industrial CT Scanners are based on 2^{nd} generation data collection geometry. Other single slice CT generations are generally not used due to operating limitations. The 1^{st} generation is too slow, the 3^{rd} generation produces excessive circular artifacts and the 4^{th} generation is too expensive. The 5^{th} generation CT geometry is not applicable to Industrial objects. It leaves the 2^{nd} generation as the choice for industrial applications. Indeed most industrial CT machines use the 2^{nd} generation data collection technique. The problem is that volume data collection using the 2^{nd} generation method is slow because it requires a separate scan for each slice along the z axis of the part. The new Tangential data collection technique produces volume CT data by design. It combines the scatter rejection and part flexibility of 2^{nd} generation with a higher speed that approaches third generation scan times.

Linear x-ray detector array systems have the best scatter rejection and photon stopping efficiency. They are usually the detector of choice for industrial applications because this higher efficiency provides a wider dynamic range necessary for the multiple densities in industrial parts. We will therefore limit our comparison to the industrial CT systems that are based on linear x-ray detector array technology.

The 2^{nd} generation system concept (single slice - multiple translate\ rotate):

The 2^{nd} generation CT scanners use a linear detector array consisting of many individual x-ray detector channels. The detector array is mounted perpendicular to the axis of rotation of object. The x-ray focal spot and the linear detector array form a fan shaped x-ray beam. The plane of the x-ray fan beam lies perpendicular to the axis of rotation of the object. Each individual detector channel forms an independent pencil x-ray beam with the x-ray source focal spot. Each pencil x-ray beam is at a slightly different angle. For example, the detector array may consist of 300 individual detectors that form a 30^0 x-ray fan beam. In this example each detector forms a x-ray pencil beam which is 0.1^0 apart from it's neighbor. To collect the data for a CT scan, the object is traversed through this 30^0 x-ray fan. In this case, the 300 detector system makes simultaneous measurements through 300 different angles in a single traverse. After a set of these 300 simultaneous measurements through the entire extent of the object, the object is stopped and rotated by 30^0 and the measurements process is repeated. In this case, six separate traverses are required to collect the minimum 180^0 data set.

During each traverse the object must traverse through the full x-ray beam to collect a complete set of data for all 300 angles. Thus, the object has to traverse a distance equal to the x-ray fan beam plus the diameter of the object. So during each traverse, many data point are collected outside the object (in air). Later during CT reconstruction process, these air reading are stripped out of the full data set because they do not contain any useful information. So during each traverse, considerable time is wasted in collecting these useless air readings.

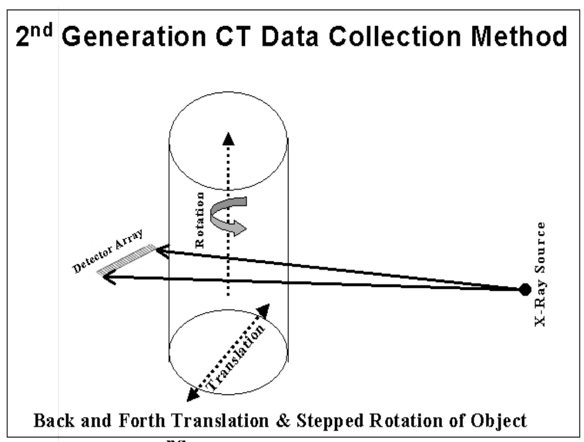

Figure 1: 2^{nd} Generation Concept

Also for each traverse, the object must travel back and forth through the x-ray beam. It requires a sequence of start, acceleration, travel through x-ray fan beam for data collection, deceleration and ultimately stop. During each traverse, significant amount of time is consumed in activities other than the actual data collection through the object. Hence in a 2^{nd} generation CT system, considerable amount of time is wasted for starting and stopping between traverses and useless data collection in air. Figure 1 shows a general concept of the data collection scheme in 2^{nd} generation CT scanner systems.

Advantages of 2^{nd} Generation CT Systems:

- It generates parallel beam data set that uses simple CT reconstruction algorithm.
- The CT images have very minimal artifact.
- Any size object can be scanned by adjusting only the translate distance.
- Linear detector array can be well collimated to eliminate out of plane scatter.
- Reasonably good scan speed can be achieved.

Limitations of 2nd Generation Systems:

- Several detectors are used to collect the CT data for each slice. There usually are variations between the response of various detectors and software corrections are used to eliminate these. Often, the software corrections do not completely remove all variations causing small mismatch at different angles in the data set. It can result in a small loss in image quality and small artifacts.
- As mentioned before, significant time is wasted in starting and stopping during each traverse.
- Also, substantial amount of data is collected outside the object causing waste of time.
- Several traverses are required to collect complete data set.
- Number of views in the data set is limited by the angular spacing between detectors. This is fixed by the design and it determines the ultimate spatial resolution limit of the system.
- The data is collected for one slice at a time and requires many slices for a volume scan.

The 3rd generation system concept (single slice or volume - rotate only):

The 3rd generation CT scanners also use a linear detector array with many detectors. The detectors are usually located on an arc that is focused at the x-ray source focal spot. Again, the x-ray source focal spot and the detector array form a x-ray fan beam. The object is located somewhere in the middle between the x-ray source and the detector array. In a 3rd generation system, sufficient number of detectors are used so that the fan x-ray beam covers the entire object. For CT data collection, the object rotates around it's own axis. For 180^0 data collection, the object rotates by 180^0 (plus the x-ray beam fan angle). For 360^0 data, the object rotates by 360^0 (plus the x-ray beam fan angle). This method only requires a pure rotation of the object, it is relatively a fast scanning technique. Figure 2 shows a general concept of the data collection scheme in 3rd generation CT scanner systems.

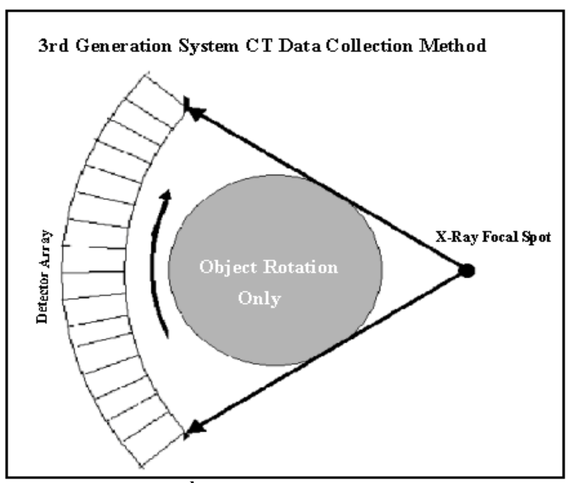

Figure 2: 3rd Generation Concept

Advantages of 3rd Generation System:

- Such a system offers faster scan speed.
- It has very simple (rotation only) mechanical motion.
- Smaller and simpler machine.

Limitations of 3rd Generation System:

- Maximum diameter of the object is limited by of the x-ray fan beam size i.e. number of detectors.
- Number of rays through the object are limited by the number of detectors covering the object. The ray spacing is determined by the angular spacing between the individual detectors. Both of these are fixed by the design, it determines the ultimate spatial resolution of the system.
- The data from all detectors is always collected. Hence, significant amount of useless data is always collected when scanning smaller objects
- Each individual detector views a tangent to a fixed circle within the object. So, even small detector variations cause circular artifacts in the reconstructed images. Small amount of detector- to-detector variations cause many circular artifacts in reconstructed image. This is

the most troublesome problem in 3rd generation CT systems. For industrial applications, 3rd generation systems are rarely used due to circular artifact problems.

- It has high cost because it requires large number of detectors to cover large objects.

The data is collected for one slice at a time and requires many slices for a volume scan.

Results:

Tangential CT (TCT) Scanner System Concept (volume - single translate\multiple rotate):

In the TCT design also, a linear array of individual x-ray detectors is used. Unlike conventional scanners, in TCT system the linear detector array is placed parallel to the axis of rotation of the object. The fan x-ray beam is formed by the x-ray source and the detector array. Now, the plane of the x-ray fan beam extends along the axis of the rotation of the object. The object is located between the x-ray source and the detector array.

For TCT data collection, the object rapidly rotates around it's own axis. Simultaneously, the object also slowly traverses through the x-ray fan beam in a direction perpendicular to the plane of the x-ray fan beam. The object continuously makes many rotations while it traverses through the x-ray beam. The combined motion is like the object rolling through the x-ray beam. A general concept of the tangential scanning is shown in figure 3.

At the beginning of a CT scan, the object is aligned so that one of its external edges touches the x-ray fan beam. To collect data set with only180^0 views, the object traverses from this edges to its center. For 360^0 data set, the object traverses from this edge to the other edge. Thus all of the data is collected only through the object. In this data collection scheme, the individual detectors collect x-ray intensity data along tangential paths of varying diameter circles within the object. Since the object simultaneously rotates and translates through the x-ray beam, the system collects data in a spiral shape (like unrolling a roll of a paper towel) in the object. Through our ThruVU Three-D (3-D display and analysis) software, thus collected raw CT data file can be simply viewed and analyzed one layer at a time.

Strengths of Tangential CT Scanning method:

- It uses a linear detector array with excellent dynamic range and scatter rejection.
- It is a true volume CT scanner system that simultaneously collects data for the entire volume of the object.
- For most part, each detector collects data for one slice of the object. Due to single detector data for the entire CT slice, the TCT system provides better noise characteristics and fewer artifacts.
- It exhibits even faster scanning speeds than a third generation system, because the data for all slices is simultaneously collected and also only the minimum needed data is collected.
- Continuous and simultaneous motions avoids time loss.
- Any size objects can be scanned. The object size is determined by the traverse distance controlled by software only.

  Data sets with any number of rays and views can be collected by changing the data collection parameters like data acquisition rate, rotation speed and translation speed. This allows the system to achieve any desired geometrical resolution.

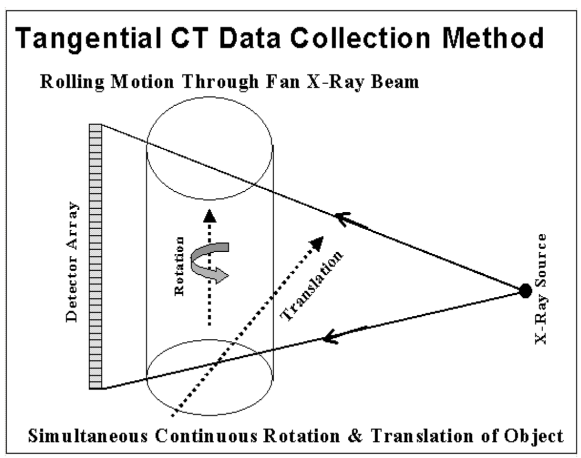

Figure 3: Tangential CT Concept

- Smaller data files are generated because tangential system does not collect useless data outside the object.

- It uses extremely simple mechanical motions. This simplifies the system's mechanical design and improves overall system reliability.
- The system easily collects conventional digital radiographic data set by just translating the object (without rotation) through the x-ray beam.
- The TCT data collection mode naturally leads to a very useful data format for image display and analysis even without CT image reconstruction.
- A high resolution CT scan of a small region of the object (inside a large volume) can be quickly scanned without interference from outside volume.
- Small (limited view) Annular data set (around the bond line region) can quickly be collected for circumferential flaws like Unbonds in rocket motors or missiles.

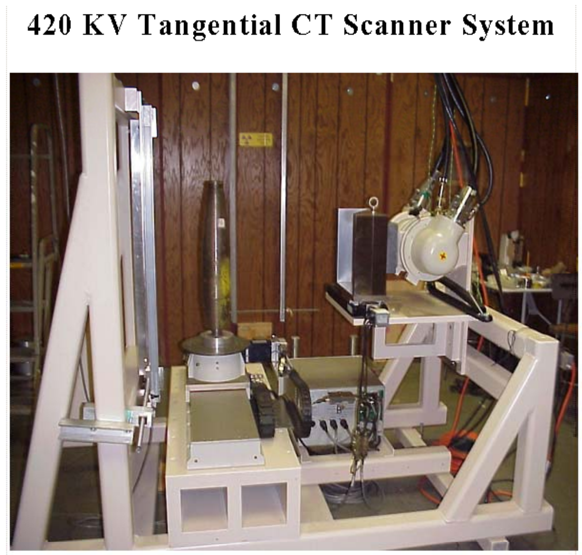

Figure 4: Picture of Tangential CT Scanner

Limitations

- Resolution in the Z direction is limited by detector spacing.

Discussion:

Volume CT Reconstruction Method:

Though not truly correct, if we view this data collection system in a very simple sense of single slice scanner, each detector collects data for one cross sectional CT slice of the object. The data for one cross sectional CT slice is collected by one detector only. All detectors of the detector array simultaneously collect data from the entire volume of the object. Different detectors collect data for different cross sectional slices of the object. The above statement is almost correct for detectors located at small fan angles. At small fan angles, common parallel beam (2^{nd} generation) CT reconstruction algorithm can be used for CT image reconstruction near the central slices.

At large fan angles (the volume away from the central slice), the common parallel beam CT reconstruction algorithm does not work well because the raw data truly travels through multiple slices. When we look at it carefully, we use a fan x-ray beam in one direction (parallel to the rotation axis) and parallel x-ray beam in other direction (parallel to traverse direction). It is in the fan beam direction, where the raw data travels through multiple slices.