Tangential scanning of hardwood logs: developing an industrial computer tomography scanner

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Abstract

It is generally believed that noninvasive scanning of hardwood logs such as computer tomography (CT) scanning prior to initial breakdown will greatly improve the processing of logs into lumber. This belief, however, has not translated into rapid development and widespread installation of industrial CT scanners for log processing. The roadblock has been more operational than economic. Currently available CT scanners were developed for medical applications, where imaging needs are very different from those in hardwood log processing. The latter is also very different from softwood log scanning needs. By examining the evolution of CT scanners, including designs and limitations, we argue that the need to scan large-size material at high throughput rates and with relatively fine resolution requires a very different approach to scanning. Tangential scanning is a viable alternative to traditional axial tomography because it offers simple mechanical operation, fast scan speeds per volume, relatively low power requirements, and no image artifacts. Initial work has demonstrated its feasibility for log scanning. Ongoing efforts have enlisted industry support to delineate operational parameters for industrial log scanning, build a technically sound prototype, and improve image reconstruction algorithms.

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Introduction

Knowledge of internal log defects, obtained by scanning, is a critical component of efficiency improvements for future hardwood sawmills and veneer mills (10). Studies have demonstrated potential value gains of 11, 14, and 21 percent (Richards et al. (12), Tsolakides (14), and Wagner et al. (15), respectively) that can be achieved by sawing logs under different log orientations and using different sawing methods. A basic presumption for the application of internal scanning to log sawing is that knowledge of internal defects will lead to choosing the best

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sawing position and method, and therefore will allow mills to realize these potential value gains.

Most scanning methods bombard a specimen with energy, either in the form of elastic waves or electromagnetic waves. Detectors measure the energy emitted from the specimen, and from this information various characteristics of the object material can be inferred. Computer tomography (CT) is one of a large number of nondestructive techniques that is in broad use today.

CT and X-ray imaging were first combined for use on medical patients beginning in the 1970s (9). Chemical similarities between human specimens and wood led researchers to consider CT scanning of wood objects. A number of investigations have examined the quality of CT images and their use for wood density and moisture content estimates and for identifying internal structures (l–4,6–8,11). Even for large objects such as logs, internal structures are readily visible in a tomograph. Furthermore, empirical evidence demonstrates that the relationship between attenuation and density is very linear in wood materials (4).

For application in hardwood sawmills, such a nondestructive testing system must (13):

- scan large-diameter logs;
- provide relatively high resolution images;
- perform scans quickly; and
- scan logs for long production shifts.

Current medical CT systems, however, have been engineered for low frequency, short duration use, which is incompatible with sawmill needs. Direct application of existing medical scanning technology would be, in most cases, prohibitively expensive and slow. Most existing industrial CT scanners are designed for quality control inspections in offline situations, or online where materials are relatively small and of limited mass (e.g., airline baggage inspection). Industrial scanning of large-volume and large-mass objects, such as logs, in an online operation demands that we investigate alternative CT technologies.

The remainder of this paper discusses the different scanning geometries commercially available today, indicating both their strengths and weaknesses. Tangential scanning (5) is proposed as an alternative methodology that can alleviate the limitations of traditional geometries and meet the demands of log scanning without excessive cost. An existing bench prototype is described along with future improvements that are needed.

Tomographic scanner geometries

Two basic types of medical and industrial CT scanners have been developed since 1972. They are: parallel and fan X-ray beam scanners. “Parallel X-ray beam scanner” refers to the method of data collection, not the shape of the beam itself. There are both first- and second-generation types of parallel X-ray beam scanners. There are third- and fourth-generation types of fan X-ray beam scanners. The following sections examine each scanner type in turn.

First-generation systems

First-generation CT scanners use a single X-ray detector (Fig. la). A pencil X-ray beam is formed by the X-ray source and the detector. This X-ray beam is traversed over the scanned object to measure the X-ray intensities through parallel paths in the object. A complete set of measurements is made through the entire extent of the object (from one edge to the other edge). After each such complete set of measurements, the object is rotated by a small angle (typically by 1° between views) and the parallel measurement process is repeated. Scanning is continued until measurements have been made through 180° of view angles.

First-generation systems have a number of strengths owing to their design simplicity:

1. They are inexpensive, because only one X-ray detector is required.
2. They can employ an extremely simple geometry and data collection scheme because there is only one detector.
3. Parallel X-ray beam data collection is easy to understand and requires relatively simple algorithms to reconstruct tomographs.
4. Use of a single detector means that there are no variations or small mismatches within various regions of the data set that can occur with multiple detectors that exhibit nonuniform performance. High-quality CT cross-sectional images can be reconstructed based on the fundamental noise and quality of the original signal alone, because no additional noise is added to the data from detector corrections.

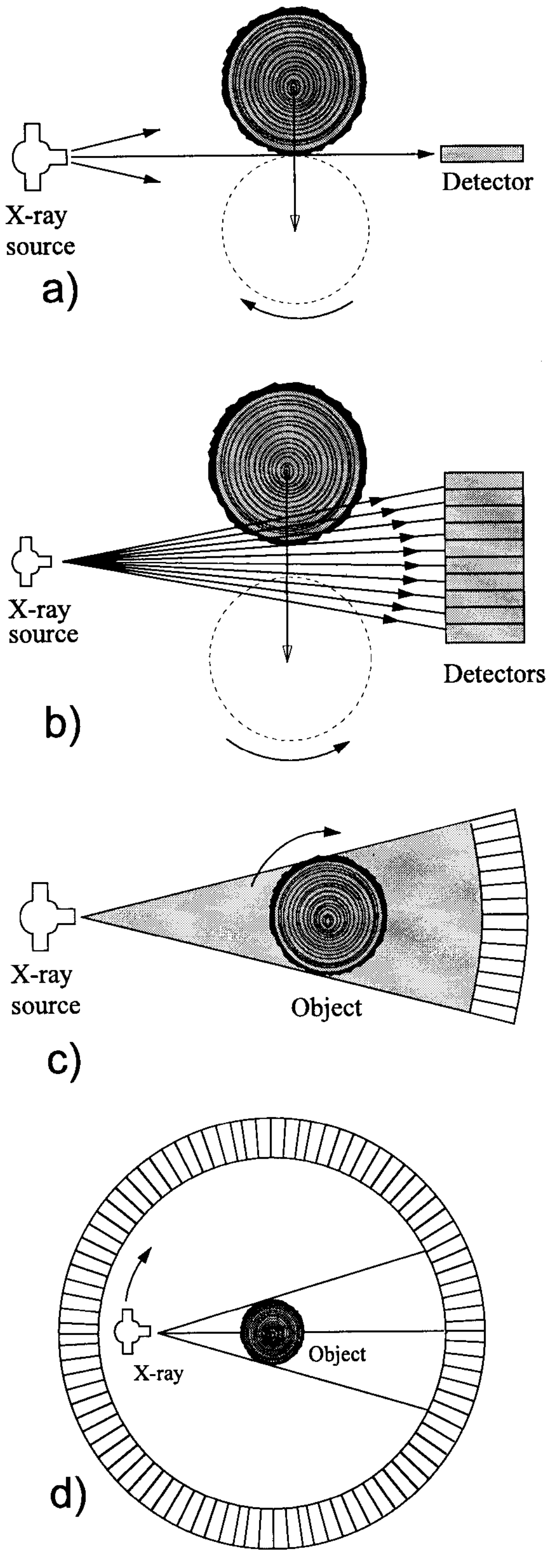

Figure 1. —*a) the first-generation CT scanner is a single-detector, translate-rotate system; b) the second-generation CT scanner is a multiple-detector translate-rotate system; c) the third-generation CT scanner is a multiple-detector, rotate-only system; and d) the fourth-generation CT scanner is a stationary-detector, rotate-only system.*

5. Any size object can be scanned by adjusting the traverse length of the pencil X-ray beam to scan larger or smaller objects.

First-generation systems are limited for industrial inspection applications because they have slow scanning speed. This occurs because:

- only one detector collects all the required data;
- time is wasted with mechanical starting and stopping; and
- data for only one slice is collected at any time.

Consequently, for most applications where time is a critical parameter, scanning times for first-generation CT scanners are prohibitively slow and first-generation CT scanners are almost never used.

Second-generation systems

Second-generation CT scanners use a detector system (array) consisting of several X-ray detectors (Fig. lb). The X-ray detectors form independent pencil beams—at slightly different angles —with the X-ray source. For example, 10 detectors may form a 6° X-ray fan. In this case, the detector system makes simultaneous measurements through 10 different angles in a single traverse. After a set of these 10 simultaneous measurements through the entire extent of the object, the object is rotated by 6° and the measurement process is repeated for 30 traverses to collect 180° of data.

Second-generation systems possess most of the advantages of first-generation systems, including simple geometry and data collection schemes, easy reconstruction algorithms, and unlimited object sizes. In addition, data can be collected by multiple detectors simultaneously, so fewer traverses are required.

Second-generation systems suffer from excessive downtime needed for mechanical operations, multiple image traverses, and single-slice data collection. Furthermore, the following disadvantages also exist:

1. Several detectors are used to collect the data, which means that there usually are variations between the responses of various detectors. Software corrections are used to adjust for detector response variations. This does not completely remove all detector variations; therefore, a small amount of additional noise is added to the data, resulting in a small loss of image quality.

2. Small artifacts appear in reconstructed CT images due to small mismatches in the data from various detectors.
3. To collect a complete set of data through all angles in the object, the inside edge of the X-ray fan beam must touch the outer surface of the object at the beginning and at the end of each traverse. Hence, a significant amount of useless data is collected at the beginning and end of each traverse.

Third-generation systems

Third-generation CT scanners use a detector array with many detectors. The detectors are usually located on an arc focused at the X-ray source. In this case, data are collected in a fanning movement, rather than parallel sweeps. A sufficient number of detectors are used in such CT systems so that the fan-shaped X-ray beam covers the entire object (Fig. lc). The object (or source-detector pair) is rotated to collect the entire CT data. For 180° data, the object is rotated by 180° (plus the X-ray beam fan angle).

Third-generation systems offer several advantages over parallel-beam systems:

1. Data are simultaneously collected through the entire object for each view.
2. The mechanical motion of the gantry is very simple rotational movement. No translation or linear motion is required.
3. Motions are continuous and hence no time is wasted in mechanical starting and stopping.
4. Scan times are quite fast due to nonstop rotational motion and many detectors collecting simultaneous data.

However, third-generation systems have numerous drawbacks, including the limitation of single-slice data collection.

1. The maximum object diameter is limited by of the number of detectors.
2. The number of X-ray views through the object is limited by the number of detectors covering the object. X-ray view spacing is determined by the spacing between the detector channels. Because both these scanning parameters are fixed by system design, scanner spatial resolution is fixed.
3. Data from all detectors are always collected. Hence, a significant amount of useless data is collected when smaller size objects are scanned.
4. Each detector views a tangent to a fixed circle within the scanned object. Thus, even small detector variations cause circular artifacts in images.
5. System cost is high because it requires a large number of detectors to ensure coverage of large objects.

Fourth-generation systems

Fourth-generation CT scanners use a detector system (array) with an even larger number of detectors. The detectors are located in a circle that surrounds the X-ray source and the object to be scanned. Because the detector array forms a circle, this system requires the greatest number of detectors. The X-ray source is located between the detector circle and the object (Fig. 1d) and is rotated in a circle to collect 180° or 360° of data.

Because of their similar geometry, third- and fourth-generations systems share both advantages and disadvantages. Advantages include:

- data are collected simultaneously through the entire object for each view;
- motions are continuous;
- mechanical motion is simple (only the X-ray source is rotated); and
- scan times are fast.

Limitations of both systems are:

- the X-ray fan beam limits object size;
- scanning small objects results in useless data collection; and
- one single slice is collected at a time.

In addition, the following limitations exist for fourth-generation systems.

1. System cost is extremely high because a very large number of detectors are required to cover the entire detector circle. Due to high cost, fourth-generation systems are rarely used for industrial applications (except where inspection failure losses are substantial, such as airport baggage explosive detection) and are becoming uncommon even in the medical industry.
2. Data are sorted in detector fans, and thus more data can be collected as the X-ray tube rotates around the object. Therefore, any number of rays can be collected through the object, but the total number of X-ray views is limited by the number of detectors. This limits image spatial resolution.

Tangential CT scanning

Design and data collection

In conventional CT scanner systems, the detector array is always placed perpendicular to the rotational axis (i.e., in the same plane as the cross-section). For tangential scanning, the detector array is placed parallel to the axis of rotation of the object (perpendicular to the cross-section). A fan-shaped X-ray beam is formed by the X-ray source and the detector array and extends along the axis of rotation of the object (Fig. 2). The detector array is much shorter (60 to 90 cm) than the log.

For data collection, the object is rotated rapidly around its own axis. Simultaneously, the object (or source-detector movement) slowly traverses through the X-ray fan beam in a direction perpendicular to the fan beam. The object can be traversed in a linear direction (parallel-beam data collection) or in a circular arc with the X-ray focal spot as the center of the circle (fan beam data collection).

At the beginning of data collection, the outside surface of the object touches the X-ray fan beam. For a data set covering 180° of views, the object is traversed from one edge to its center. The X-ray fan beam passes through one edge of the object in the beginning of the scan, and the beam passes through the center of the object at the end of the scan. For a 360° data set, the object is traversed from one edge to the other edge.

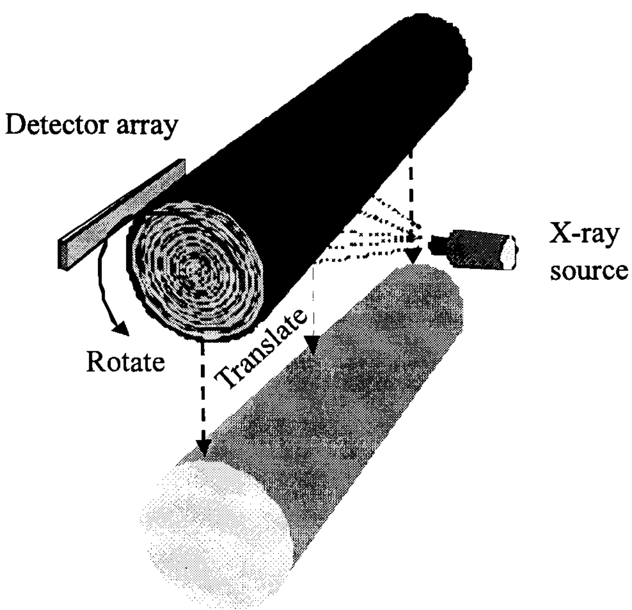

Figure 2. —*A conceptual view of the tangential scanner shows a log that rotates and translates, a detector array parallel to the axis of rotation, and an X-ray source.*

As the object traverses through the X-ray beam, the detectors collect X-ray intensity data along tangential paths of varying diameter circles. Because the object simultaneously rotates and translates through the X-ray beam, tangential scanning collects data as if the object is a roll of paper being unspooled a single layer at a time. In a log context, this would be similar to peeling veneer (Fig. 3).

For most of the X-ray beam, each detector collects data for one cross-sectional slice of the object. In addition, the entire data for one cross-sectional CT slice is collected by only one detector. As one moves toward the edges of the fan beam, however, multiple detectors collect data for a slice. For these edge slices, a 3D-reconstruction algorithm will be needed to generate tomographs reliably. All detectors in the detector array simultaneously collect data to scan an entire volume of the object. The number and spacing of detectors determines how many tomographs (and their pitch) can be collected simultaneously.

Tangential scanning should not be confused with spiral scanning. The latter uses traditional CT geometry—augmented with continuous specimen translation—to obtain continuous tomographs. Tangential scanning uses a new scanner geometry to collect multiple tomographs simultaneously in a tangential fashion.

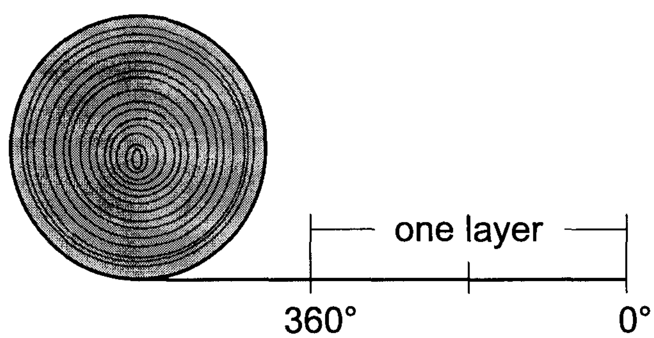

Figure 3. —*The flow of data collected by tangential scanning can be viewed as similar to unspooling a roll of paper or peeling veneer.*

Strengths of tangential scanning

For industrial applications, the improved geometry of tangential scanning provides some important advantages over existing scanning geometries.

1. Tangential scanning is a volume CT scanning system that simultaneously collects data for the entire volume of an object. Data for many cross-sectional slices are simultaneously collected. The number of cross-sectional slices is equal to the number of detectors in the linear array.
2. Tangential scanning has all the image quality advantages of a single-detector system because most tomographs are generated using data from a single detector. Due to single-detector data collection, tangential scanning provides better noise characteristics without artifacts. Even when used in fan beam data collection mode, no circular artifacts are generated in the images, because only a single detector is used for each slice.
3. Scanning speeds are even faster than third- and fourth-generation systems because only the minimum amount of data is collected for an object of any size, and no time is lost in waiting for slice-to-slice movement because multiple slices are collected simultaneously.
4. Data are collected only from one edge of the object to the other edge; no useless data is collected outside the object. This results in smaller data files and faster reconstruction, especially important for large volumes such as logs.
5. Data sets with any number of rays and views can be collected by changing the data collection rate or rotation and translation speeds. This allows the system to achieve any desired geometrical resolution. The number of rays through the object is equal to the number of rotations during data collection. The number of rays through the object can be increased to achieve better spatial resolution, or they can be decreased to reduce scan time. Thus, the tangential system can collect data as if it has any (variable) number of detectors. Similarly, the number of views through the object is equal to the number of data points collected during a single rotation. Again, it can be increased for better spatial resolution or decreased for better scan time. Thus, the tangential system can collect data as if it has any number of views.
6. Extremely simple mechanical motions are required, which simplifies the system's mechanical design and improves overall system reliability.
7. Data collection in a tangential mode naturally leads to a very useful image format for display and analysis even without time-consuming image reconstruction. Data are naturally collected in tangents, which produces sinographic displays in which each layer (360°) of the data is easily unrolled and viewed unfolded.

The only currently obvious limitations to tangential scanning are the unavailability of fast and effective reconstruction algorithms and the fixed pitch of cross-sectional tomographs (limited by detector width and spacing). Improved reconstruction algorithms are under development, however. Detector spacing can be fixed at a relatively small distance, and then particular detectors (every other detector, every third, etc.) can be read to obtain the desired pitch.

Current tangential scanning prototype

Omega International Technology, Inc. has designed and fabricated a full-size experimental apparatus to collect data from logs up to 15 inches in diameter and 2 feet in length. This includes a mechanical gantry with simultaneous translation and rotation of the log, a 128-channel detector array, a 300-kV X-ray generation system, fan beam X-ray collimation, and data collection, as well as data analysis and display software. A photograph of the apparatus appears in Figure 4.

X-ray generation. —The 300-kV X-ray tube is mounted on one side of the bench prototype and the detector array on the other side. Except for a l/8-inch-wide slit opening for the primary radiation beam, the X-ray tube head is surrounded by at least 4-inch-thick lead shielding to reduce X-ray radiation in the surrounding area. This shielding not only reduces ambient radiation levels but also eliminates the production of most scatter (unwanted stray) radiation. The detector array is also surrounded by at least 2-inch-thick lead shielding. This shielding around the detectors reduces most of the scatter radiation. The

X-ray tube source and the detector array collimators form an X-ray fan beam traveling in a vertical direction. The axes of the source and detector slits were precisely aligned to each other by a laser beam.

Detector array. —The detectors are modular in construction. Each crystal scintillator is bonded to a separate photo diode. The detectors capture X-ray photons in the scintillator, converting them to light and then to an electrical output signal correlated to the photons captured. The signal from the photo diode is then amplified and multiplexed for transmission to the computer. Individual detector modules are laid side by side (currently 8 mm apart) to create a large linear array for industrial applications.

Results

In a typical experiment, the log rotates continuously with a rotation speed of about 10 seconds per rotation. The linear speed of the system was set to about 80 seconds per inch. There are significant variations in both the translate and rotate speeds. Nevertheless, this apparatus allowed us to collect 1024 X-ray angular views per rotation and 8 rays per inch through the log during a typical tangential scan.

The data collection routine is started manually and collects one line of data (128 readings, one from each detector) for each trigger pulse received from the encoder of the rotary motion. As the data is received by the computer, it makes inline offset and gain corrections on each reading for each detector before storing the data.

A typical tangential scan with 15-inch translation (360°) of the log through the X-ray beam produced approximately 32 MB of data. Other larger data sets were also collected with slower motion in the translate stage, which generated more rays per inch. Filtered backprojection (of the sinogram data of an individual detector) was performed to reconstruct an individual CT slice. An example CT reconstructed image from a slice of a softwood log appears in Figure 5.

Errors in the rotation speed were overcome by the encoder system. The 128-channel detector system includes logic circuits to collect data when triggered with an external pulse, such as from the position encoder on the rotary motion stage. This approach synchronized data collection to the angular orientation of the log, independent of variation in rotational speed. Small positional problems due to speed errors in the translate stage were ignored.

Conclusions

The initial bench prototype has demonstrated feasibility for tangential scanning of logs. Nevertheless, improvements must be made to the

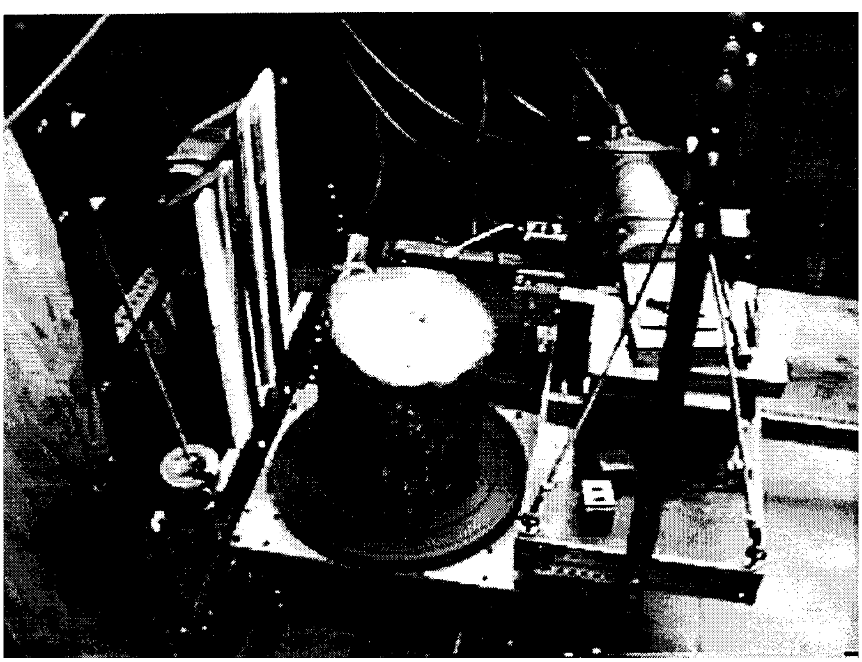

Figure 4. —*A bench prototype of a tangential scanner with a log section resting vertically on a turntable that translates forward and back. A detector array is mounted vertically on the left, and the X-ray tube is mounted on the right.*

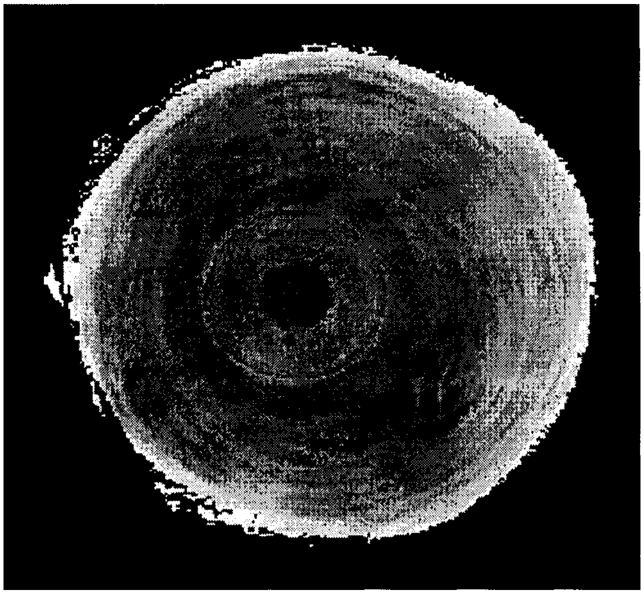

Figure 5. *—A CT reconstructed image of a log allows identification of heartwood and a knot, but limited discrimination of other features.*

current apparatus before a full-scale prototype can be designed.

The present rotation system uses a very crude bearing mechanism with significant runout. We need to include a good bearing in the system for more precise rotation. In addition, the rotational speed of the initial prototype is limited to about 10 seconds per rotation. By converting to a direct drive system, both speed and accuracy can be improved.

In the present system, 1024 encoder pulses per rotation trigger the detector array, and therefore 1024 angular views of the log are collected. For a CT system used in log scanning, this number is excessive and leads to more data than is really needed. The number of pulses should be reduced to 600 per rotation. This will provide 600 angular views, which is an excellent number of angular views for a CT system with about 200 rays.

The current X-ray tube experiences considerable energy intensity drift. It will be necessary to design, fabricate, and install a high-performance, low-noise, single-channel X-ray detector that can continuously measure the intensity of the X-ray tube. These reference detector measurements can then be used to correct the entire data set to eliminate the effect of the X-ray intensity drifts.

Existing software can also be extended to include the following:

- automatic preprocessing of individual detector sinogram data (using geometrical parameters, etc.);
- automatic filtering of sinograms to prepare for filtered backprojection;
- automatic backprojection of filtered sinogram data to reconstruct individual CT images; and
- compilation of all CT slice images into a set of files so that they can be viewed as a three-dimensional volume and analyzed by existing CT software.

The unique geometric design of tangential scanning gives it cross-generation advantages without their inherent limitations, and permits collection of multiple slices simultaneously, These characteristics make it particularly effective for high-throughput, large-volume industrial inspection of hardwood logs.

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