CT IMAGING, DATA REDUCTION, AND VISUALIZATION OF HARDWOOD LOGS

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ABSTRACT

Computer tomography (CT) is a mathematical technique that, combined with noninvasive scanning such as x-ray imaging, has become a powerful tool to nondestructively test materials prior to use or to evaluate materials prior to processing. In the current context, hardwood lumber processing can benefit greatly by knowing what a log looks like prior to initial breakdown, Previous research has indicated that CT imaging of logs can pay for itself in medium- and high-volume sawmills. Nevertheless, numerous implementation issues remain. This paper discusses several of these, First, x-ray imaging parameters for various species, defect resolutions, and defect contrasts need to be better understood. Second, the CT data collected is voluminous and needs to be condensed for application to subsequent decisionmaking. Third, because CT imaging produces spatial information, there needs to be some way to visualize that information to allow saw operators to improve lumber value recovery.

INTRODUCTION

During hardwood log breakdown, profit-critical decisions are made by the sawyer that cannot be undone by downstream processing operations. This observation suggests that targeting sawlog breakdown improvements can drastically increase lumber value recovery. The sawyer uses log shape, bark indicators of internal defects, and knowledge of lumber grades to make sawing decisions. While sawyers are highly skilled in this task, studies (Richards, et al. 1980, Tsolakides 1969, Wagner, et al. 1990) have shown that the lumber value of logs can be improved 20% or more by selecting the proper sawing strategy. However, more information needs to be available during the log breakdown operation to enhance the sawyers ability to produce high-value boards.

Sawlog breakdown decisions become even more critical when one considers the value and quality of the wood resource. For man y hardwood mills, producers feel that log costs represent up to 75% or more of lumber production costs (Steele, et al. 1992). Wasting any amount of such a valuable raw material will reduce profit margins. Also, hardwood sawlogs in the eastern U.S. tend toward small diameters and low quality. More than 58% of sawtimber volume in the eastern U.S. is in the 12, 14, and 16 inch diameter classes (Powell, et al. 1992). Additionally, more than 60% of hardwood tree volume in Virginia’s Northern Mountain region (U. S.) is in tree grade #3 (U.S. Forest Service scale) or below (Johnson 1992). Cutting high-value lumber from smaller diameter logs of low quality requires even greater skill by the sawyer because each cut has a greater impact on yield.

A tacit assumption for the use of internal log scanning technology is that the potential value gains referenced above can actually be realized by knowing what a log looks like inside. In theory, a sawyer would be able to select the best breakdown method based on internal defect size and location, in addition to external log geometry. Future efficiency improvements in sawmills will depend on the ability to apply this type of defect information (Occeña 1991, Schmoldt 1993).

While economic analyses indicate that lumber value gains can offset scanning costs (Chang 1989, Hodges, et al. 1990), there are several technological hurdles that must be overcome for the application of computer tomography (CT) scanning to sawlogs. First, we must determine what scanning parameters are required to adequately image logs of different sizes and species, with different image resolution requirements, and with different levels of image contrast. Second, there must a way to condense the tremendous amounts of data that are generated by CT imaging, so that only critical, decisionmaking information is retained for downstream processing. Finally, the CT data need to be visualized in a way that conveys their spatial nature and that is natural for the sawyer to understand. These issues are examined in the following sections, preceded by an introduction to CT and x-ray imaging.

COMPUTER TOMOGRAPHY

In general, nondestructive evaluation (NDE) techniques attempt to examine some object of interest by scanning in a manner that does not disrupt the physical or structural integrity of the material. 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. CT is one of a large number of NDE techniques that are in broad use today.

Computed Images

The initial description of the mathematical principle underlying computer tomography occurred in 1917 (Radon 1917). Basically, it is a method for calculating characteristics of points in a 2-d plane by measuring an infinite number of ray-sums passing through the 2-d area including those points. This can be seen in Figure 1, where the value of each point can be estimated by combining the ray-sums that pass through each point from many different angles. Better differentiation between points in the plane occurs with more ray-sums per point, and higher resolution occurs by using smaller thickness rays.

A variety of sensing techniques have been used to produce ray-sums in the scanning of materials. These include: ultrasound, x-rays, nuclear particles, and microwaves. X-rays have been the preferred sensing method because

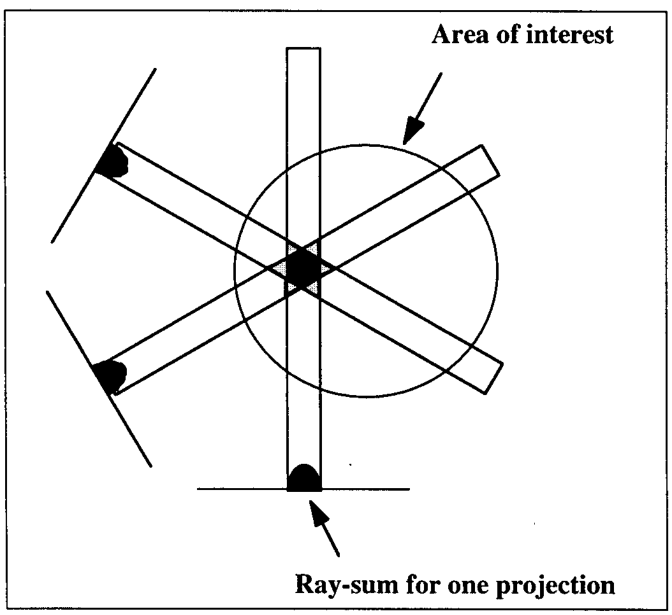

Figure 1. Computer tomography mathematically generates points in a 2-d plane by measuring many ray-sums for each of the points in the area of interest.

they are relatively easy to generate and they have high energies making them attractive for penetrating large or dense specimens.

X-ray Imaging

The loss of x-ray intensity, or x-ray beam attenuation, can be determined by knowing initial beam intensity and by measuring beam intensity after it has passed through a specimen. Attenuation results from each small volume that a ray passes through on its path through the specimen. Each small volume has an associated attenuation coefficient. Attenuation coefficients are dependent on material density, material atomic number, and ray intensity. If ray intensity is kept constant during the course of scanning and the material being scanned has a relatively homogeneous atomic number, then the attenuation coefficients are directly related to material density. Theoretically, then, x-ray attenuation is affected by the density of the material through which rays pass.

CT imaging produces images that lie in the same plane as the x-ray beam (Figure 2). By measuring many simultaneous ray-sums and continually rotating the specimen (or source-detector pair), a detailed 2-d, cross-sectional image or tomograph is generated. This technique is illustrated in Figure 3 using a log specimen. By taking successive 2-d images it is possible to determine the internal appearance of a 3-d object. Computed tomography and x-ray imaging were first combined to image medical patients beginning in the 1970's (New, et al. 1974). Body components that differ in density by 1-290 are easily distinguished in tomographic images. An image consists of a rectangular array (often square) of picture elements (pixels), where each pixel represents the attenuation coefficient of a small volume. This volume is determined by the size of the image pixel and by the thickness of the x-ray beam.

Radiography, in contrast, generates images, or photographs, by sending x-rays simultaneously through a large volume of a specimen. The rays are perpendicular to the imaging plane. A volumetric photograph results, no computer tomographic calculations are made. The technique and resulting image is illustrated in Figure 4.

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 the identification of internal structures (Benson-Cooper, et al. 1982, Birkeland and Holoyen 1987, Burgess 1985, Cown and Clement 1983, Davis and Wells 1992, Miller 1988, Onoe, et al. 1984, Shadbolt 1988). All these investigators have found that CT images provide a large amount of information

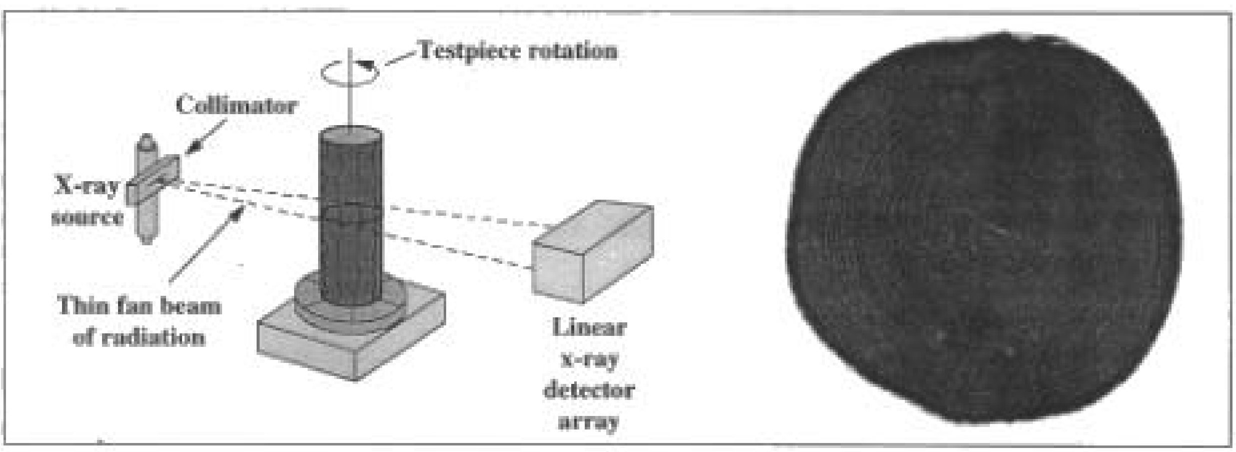

Figure 2. In computer tomography, the imaging plane is parallel to the x-ray beam and generates a cross-sectional image.

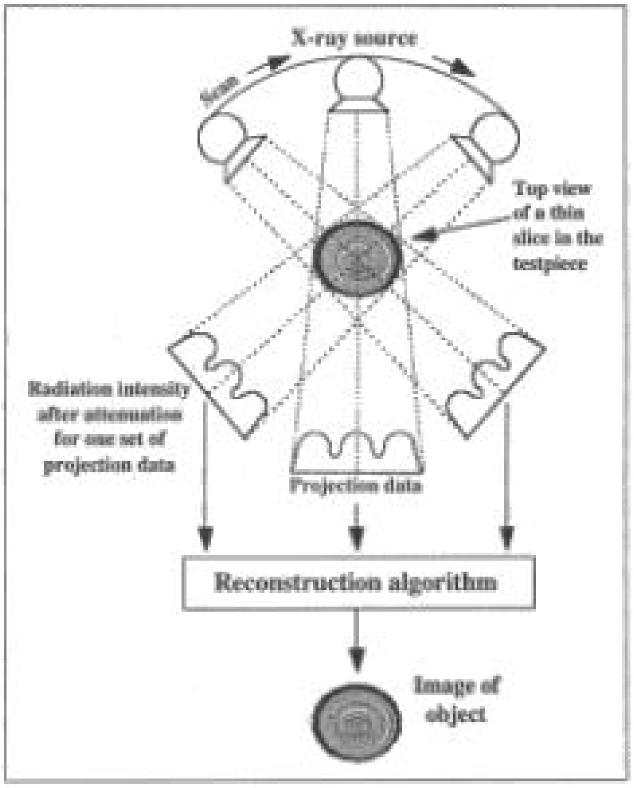

Figure 3. The combination of computer tomography and x-ray imaging allows one to generate detailed cross-sectional images of a scanned object.

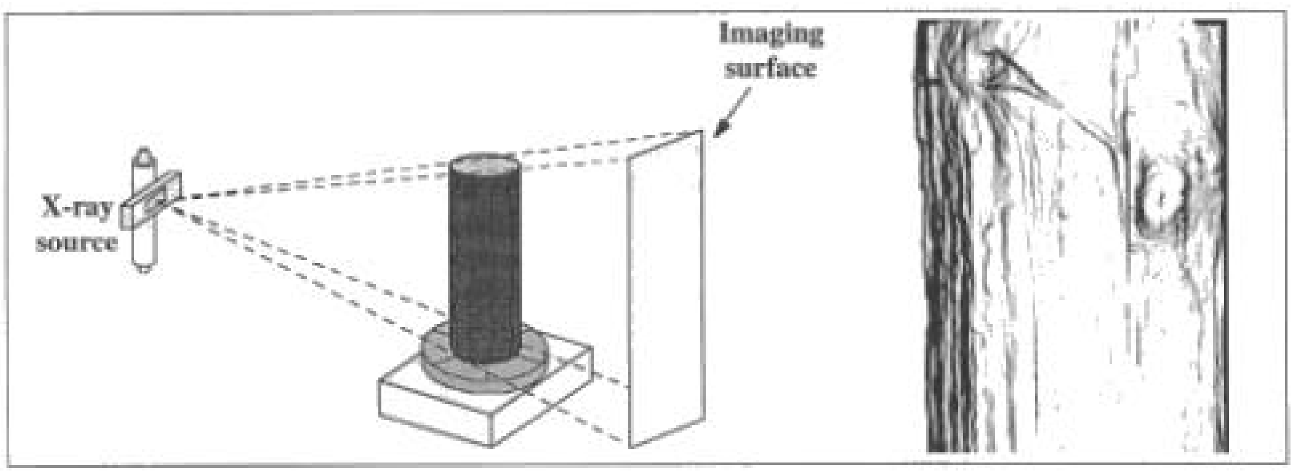

Figure 4. In radiography, the imaging plane is perpendicular to the x-ray beam and generates an image similar to the "chest x-ray" at the right.

about the internal characteristics of wood. Even for large objects, such as logs, internal structures are readily visible to someone examining a tomograph.

Empirical evidence demonstrates that the relationship between attenuation and density is very linear in woody materials (Davis and Wells 1992, Shadbolt 1988). Each pixel (a small area in the CT image that actually represents a small volume, or voxel) of a CT image has an associated CT number which describes that small volume's attenuation of transmitted x-rays, relative to the attenuation of a similar volume of water. Therefore, CT numbers can be broadly interpreted as density measures. Because knots, bark, decay, sapwood, heartwood, voids, etc. have different densities, these features can also be distinguished by CT numbers on tomographs. Pixel-by-pixel CT numbers can be used in subsequent image processing steps to segment and identify relatively homogeneous regions.

Scanner Geometries

CT scanning of an object can be performed using a number of different scanner geometries. A first-generation scanner appears in Figure 5. This scanner architecture produces good results and is inexpensive and relatively easy to construct (Davis and Wells 1992). A source/detector pair move in unison past a specimen. At discrete uniform distances, the source emits x-ray photons which are sensed by the detector. Because the incident photon rate from the source is known and the photon rate at the detector is measured, the attenuation of x-ray transmission can be calculated for the small volume of the specimen that this ray passes through. These measurements are made through a single plane of the specimen. Then the specimen is rotated through some small angle and the source/detector move through the same plane again. When the specimen has rotated through 180°, then a 2-dimensional CT image can be reconstructed from the attenuation values.

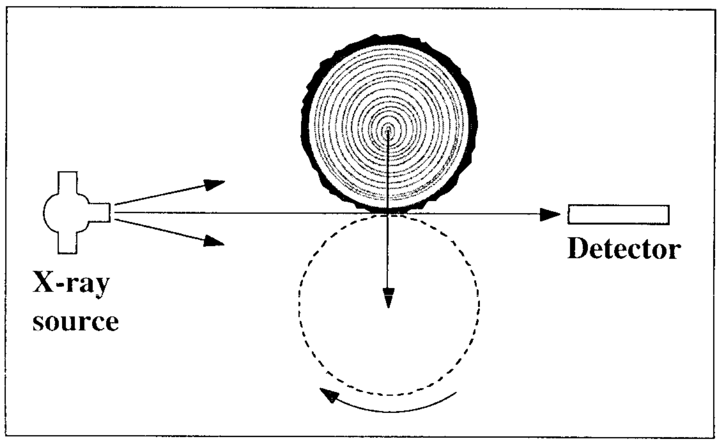

Figure 5. A first-generation CT scanner is a single-detector, translate-rotate system.

Many other scanner geometries have been developed since that time. These include multi-detector, translate-rotate systems, rotate-only systems, and stationary-detector, rotate-only systems (Figure 6). Medical applications use rotate-only systems. Each geometric configuration has certain advantages in terms of speed and artifact generation that make it advantageous for certain applications.

Initial use of CT for industrial applications involved the use of medical systems. Medical systems, however, are limited somewhat by x-ray energies and by x-ray tube cooling requirements. True industrial systems, on the other hand, require: (1) higher energy x-ray sources, (2) accommodation for larger specimens and denser specimens, (3) higher resolution, and (4) operation in industrial environments. In the last 15 years, true industrial systems have been developed, but their use is still limited within production operations.

Scanning Parameters

There are many factors that influence the operating parameters of a scanner. Little, if any research, however, has examined these factors in relation to scanning wood. The scanning parameters that are important are (1) x-ray tube techniques, (2) scan thickness, and (3) scan frequency.

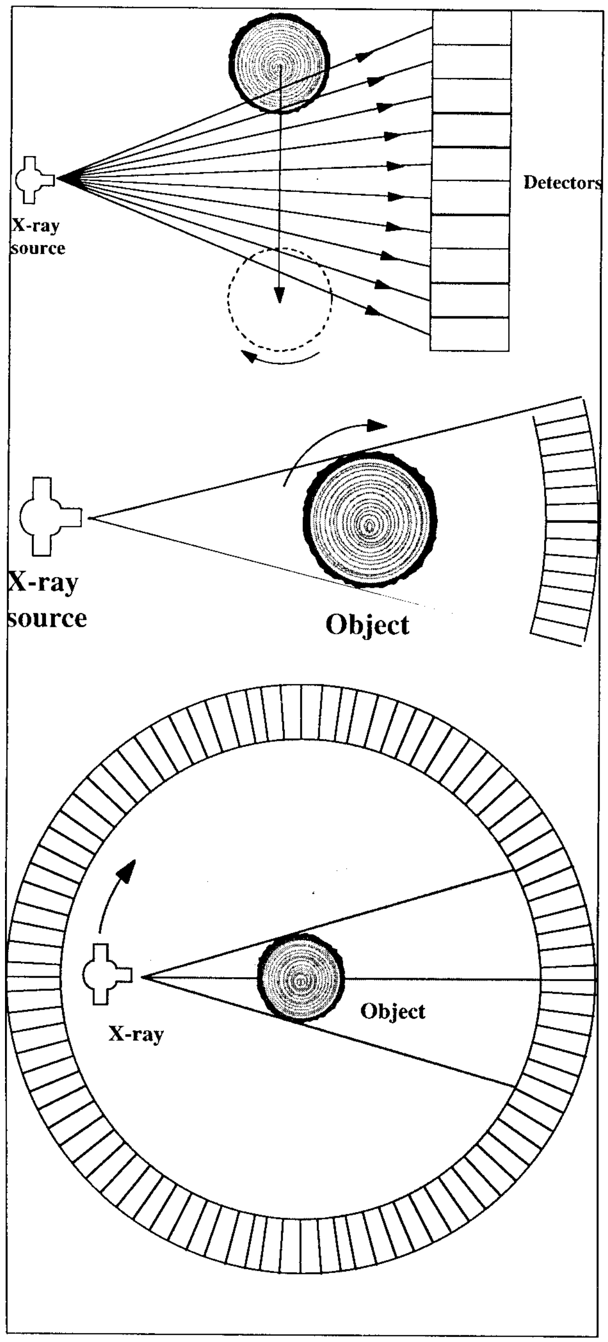

Figure 6. Three additional CT scanner geometries are illustrated: multi-detector, translate-rotate (top), rotate-only (middle), and stationary-detector, rotate-only (bottom).

Tube techniques determine how many photons of radiation are transmitted in a fixed time interval (amperage) and what energy those photon possess (voltage). Higher energy photons are able to penetrate thicker specimens. Also, by generating more photons in a fixed time period, reliable photon counts can be achieved more quickly and therefore permit faster scanning. Nevertheless, higher power tube techniques result in shorter tube life and require greater tube cooling efficiency. When cooling capacity is exceeded, scanning must be suspended, thereby slowing overall scanning throughput. Higher power tube techniques also cause a loss of contrast because a large number of photons reach and saturate the detectors, regardless of material density. Then, small changes in specimen density cannot be distinguished. Therefore, tube techniques contain tradeoffs between scan speed, cooling capability, and image contrast.

The pixels in each CT image represent the average attenuation coefficient for a small volume. This volume is determined by the resolution of each pixel in the image and by the thickness of the scan. Pixel resolution is determined by the field of view for the scanner, which is dependent on the source-detector distance and the number of detectors. Pixel dimensions are usually square and in the range of 0.9-3.0 mm. The amount of collimation fixes the scan thickness. Values of 1-20 mm are common. As scan thickness is reduced, higher power tube techniques are required to achieve reasonable photon count rates. As noted above, this increased tube power reduces tube life and increases cooling requirements.

The scanning rate, or frequency, specifies how many cross-sections are generated per unit of longitudinal distance of the specimen. Scans can be continuous, as in helical scanning or adjacent scans, or there can be substantial gaps between successive scans. Higher scan frequencies give better coverage of the specimen, but take longer to scan a specimen and result in shorter tube life and greater tube heating per unit time.

Many different factors related to logs influence these scanning parameters. First, different species vary significantly in the amount of x-ray power (voltage ¥ amperage) required to penetrate a fixed log diameter. Second, log diameter for a particular species will impact the power required, also. Third, the level of contrast (distinguishable changes in density) necessary to adequately discriminate various defects has not been established. This may even vary by species. Fourth, the size of defects that need to be distinguished will determine voxel size, i.e. image resolution and scan thickness. Defect size may also partly affect scan frequency. Fifth, the end use of the scan information may partially determine voxel size and scan frequency. If only course information is required, to sort logs for example, then voxel dimensions can be quite large and scan frequency can be quite low. If, on the other hand, fine detail is required to make log breakdown decisions, then it may be necessary to reduce voxel size (or image resolution size only) and increase the scan frequency to ensure that most defects are completely imaged. Finally, all characteristics of the logs and the information required for processing will affect scanning throughput speeds. Speed is important to the extent that scanning fits into the overall production context of the sawmill.

DATA CONDENSATION

Generating CT images produces tremendous amounts of data. For example, depending on resolution and frequency of scans, a single 12 ft. log may produce 20-800MB or more of image data. Obviously, it is unrealistic to expect anyone to gain much insight into the 3-d appearance of an entire log by viewing a sequence of 2-d CT images. Fortunately, CT data contain a large amount of redundancy, which can be exploited to condense the data into a form that is more manageable and usable.

Instead of voluminous amount of CT data, these cross-sectional images must be condensed and integrated to form a solid geometry view of the log and its internal features. Only those internal features of a log that are important for subsequent processing need to be identified. These features are the defect areas within the log.

Each defect is relatively contiguous and each defect type is fairly homogeneous with respect to density. Consequently, over the past 15 years researchers have begun to develop automated methods to automatically interpret CT images (Funt and Bryant 1987, Hopkins, et al. 1982, McMillin 1982, Schmoldt, et al. 1996a, Zhu, et al. 1996). Once different internal log defects can be automatically detected then it becomes a relatively straightforward task to integrate those views into a 3-d rendering of the log.

With the exception of Schmoldt et al. (1996a), most of these efforts to automatically interpret CT imagery have been limited in their usefulness. First, they have been feasibility studies designed to test the concept of automated defect identification and labeling, and to try several different algorithmic approaches, first on softwoods and later on hardwoods. Second, there have been few valid statistical tests of how accurately these approaches identify and label defects. Most have used a single data set or a single pair of training and test sets. Third, there has been no effort to develop methods that operate in real time. Earlier methods were not timed for speed or their computational times were unacceptably slow. Automated labeling needs to operate nearly as fast as scanning, so that large amounts of scan data do not have to be archived for later data processing. Only interpreted images should be retained for subsequent decisionmaking.

The defect detection algorithm that we have developed (Schmoldt, et al. 1996a) overcomes these 3 limitations. It is able to label an entire CT image (containing 64K pixels) in 1-2 seconds, it can be trained to work for any species, and it has a statistically valid accuracy rate of 95% at the pixel level (prior to post-processing). Visual assessments indicate that post-processing operations improve accuracy further. An example of how well the defect classifier works is illustrated in Figure 7. After this defect detection algorithm is applied to each CT image for a log, slice-by-slice data regarding each defect and the log perimeter can then be used to generate "glass log" images for viewing by a sawyer prior to log breakdown.

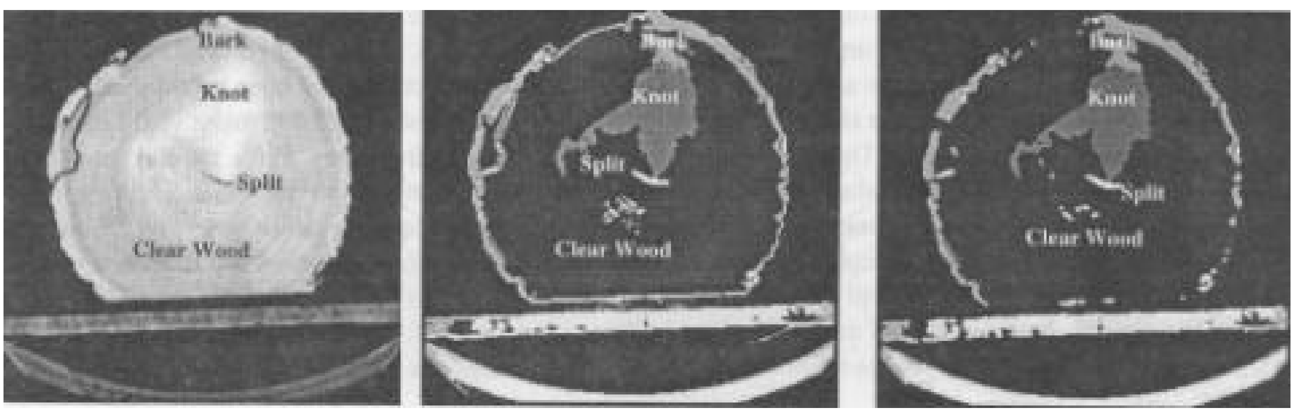

Figure 7. The CT image (left) is initially labeled (middle) by an automated defect recognition algorithm. The last image (right) is the final labeling following some post-processing.

DATA VISUALIZATION

As noted previously, there is limited value to showing the sawyer a series of CT images of a log. It would be nearly impossible for the sawyer to relate those individual images to an overall picture of the log, its external geometry and its internal defects. There are instances, however, where viewing CT data, itself, can be useful. For example, one could simulate the appearance of veneer by generating a longitudinal cut through CT cross-sectional images (Figure 8). Such a simulator was developed by Schmoldt et al. (1996b), but, most likely, this is

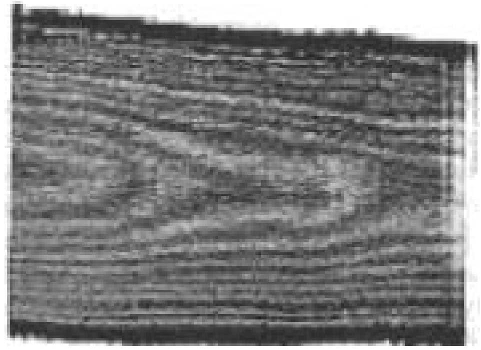

Figure 8. Simulated veneer can be generated by taking corresponding lines from consecutive CT images to produce a longitudinal plane through the log.

a singular application of CT imagery, wherein images are used directly. In all other cases, it will be necessary to condense the data prior to visualization.

The first step in aiding the sawyer's ability to achieve more optimal log breakdown is to provide a 3-d image of the log as the sawing occurs. This view would appear on a computer screen and show the log exterior and its clear wood areas as transparent or translucent. Defects would appear opaque and color coded. The log could be marked with a lead tag so orientation of the log and its computer rendition could be registered.

Additional enhancements to this initial rendering step can be imagined. First, it would be possible to couple the computer rendering of the log and its orientation on the carriage. In this way, the sawyer could control log positioning by manipulating the computer rendition, or could position the log manually and see the new orientation reflected in the computerized rendition. Both manual and computer positioning might be useful. Second, by coupling log positioning and rendering orientation, log breakdown may be reflected in the computer rendition. If kerf thickness and variation is known, the computer rendition could be updated easily to reflect each board removed. Third, it might be possible for the computer to suggest a best opening face to the sawyer and automatically position the log for that cut, subject to sawyer override. Fourth, by incorporating a computerized, lumber grading program it would also be possible for the computer to suggest the next face to cut during grade sawing. These last two possibilities are moving toward automated decisionmaking, wherein the computer is aiding, or making, sawing decisions for the sawyer.

This last step moves beyond visualization and represents the final transition toward optimal log utilization. Here, the sawyer would only monitor sawing operations, and would otherwise be uninvolved in making actual log positioning and cutup decisions. Because the computer knows the log's geometry and the location of defects and can position the log, it should also be able to calculate the best sequence of sawing cuts to optimize the log's value. It would do so by knowing: (1) how to grade lumber, (2) how each board should be edged and trimmed, and (3) what the current prices are for different lumber grades. While this final step is somewhere in the future, all the necessary technology pieces are nearing completion, so automated log breakdown will arrive eventually. An obvious limitation to automated log processing using CT imagery, however, is that not all lumber grading defects can be detected using density information only. Consequently, even with this level of sophistication, log breakdown cannot be optimal.

CONCLUSIONS

Scan thickness, scan frequency, image resolution, image contrast, and x-ray tube techniques will vary by wood species, by log diameter, and by wood processor needs for internal information. These variables of the wood and the wood processor, that drive the selection of scanner parameters, may vary from day to day in a particular sawmill. This means that a scanner implementation for hardwood sawmills will need to be flexible and quickly reconfigurable as needs change. There needs to be research conducted that assesses how these driving variables affect scanning parameters. At this point in time, we can only make guesses about the interactions of a single driving variable and one or two scanning parameters. Eventually, we will need to take into account all the variables simultaneously. Ultimately, the range of scanning parameters that need to be accommodated within a scanner configuration will determine final scanner complexity and cost.

The ability to scan logs quickly and to condense the CT data simultaneously, i.e. interpret images, is absolutely essential. These NDE operations must operate close to log processing speeds for them to enhance mill productivity. Nevertheless, it may not be necessary to perform scanning in-line with other mill operations. Because it is very likely that a scanner will be enclosed in its own structure, separate from the sawmill, logs can be scanned in an off-line mode with pertinent data stored for later use. Such a scanning enclosure will allow close monitoring of conditions in the immediate scanner environment. Its location in the log yard, then, means that scanning can be used not only to precede log breakdown, but also to buck roundwood and to sort logs.

Installed sawmill scanners must accommodate large diameter material. For most mills, however, there is some distribution of log diameters that is typical for their supplies. Therefore, it may not be critical to be capable of scanning the full range of log diameters that a mill processes. Chances are that if 95% of the log volume can be scanned then a mill will be able to recover scanning costs and increase their profits.

At some point, scanned information must be integrated with mill operations. That is, it must improve breakdown at the headrig. Initially, at least, this can be most easily accomplished by providing the sawyer with a natural and sentient form of the CT data. This suggests that a picture with spatially referenced information can be very beneficial. The concept of the “glass log” has a great deal of appeal for this. The visual nature of this representation is comfortable for the sawyer while at the same time increasing knowledge about the log’s internal nature. This can be the first step in optimizing and automating the log breakdown operation.

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