Modelling of Subalpine Fir Tree Stems Using Industrial Computed Tomography (CT) Imaging and Simulated X-Ray Scanning

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Summary

The growing pressure from steadily rising timber costs and declining wood supply make it essential that application of internal log scanning technologies be actively pursued to maximize use of underutilized timber resources, such as subalpine fir. Two main needs must be satisfied for effective integration and efficient utilization of subalpine fir stems/logs. First, development of a tree model using data obtained from an internal log scanning method that can describe every log and stem by its properties in detail for research purposes. Second, as optimized utilization of the raw material in a sawmill requires knowledge of the properties of the individual logs, it is also necessary to assess feasibility of integrating new equipment for scanning the interior of logs that enable measuring internal properties of logs and stems with acceptable levels of speed and accuracy.

This report describes the design and implementation of a new surface-volume integrated tree stem model, CTSTEM, for measuring and visualization of three-dimensional (3D) properties of subalpine fir stems from X-ray images based on various projections. CTSTEM has two main components. Using full scale X-ray projection (CT) data, the first component of CTSTEM represents a subalpine fir tree stem using five modelling units, which closely resemble the real stem structure of the trees: shape, sapwood boundary, knots, branch segment, and wetwood. Design of this component consists of two primary phases. First phase comprises of the segmentation of a single CT image slice, which results in the extraction of 2D defect-like regions. The second phase comprises of the correlation of the 2D defect-like regions across CT image slices in order to establish three-dimensional (3D) support. The 2D defect-like regions with adequate 3D support are labeled as true defects. The 3D reconstruction and visualization of the modeling units is based on the volume-surface-integrated modeling concepts. The 3D output of the model agrees with manually measured properties.

The second component of CTSTEM represents logs based on parameterization (simulation of signals) of the CT images based on fan-beam and cone beam geometry. The basic idea is based on the principles of CT, with the exception that only three fan-beam and cone-beam projections are used. The aim was to simulate principles of industrial X-ray Log Scanner based on three fixed and cone-beam X-ray sources. Using the simulated signals, the component creates x-ray images of the modeling components logs. Exact reconstructions of the internal components from three projections were not possible. However, good estimates for the size and co-ordinates of the knot and wetwood patterns were achieved with the method.

The most important conclusions of this project were that: CT scanning is a powerful research tool for acquiring data for the modelling and visualization of different stem properties of subalpine fir species. CTSTEM is capable of automatic detection, 3D modeling, visualization and calculation of parameters of the subalpine fir modelling units. It provides a synergistic analysis capability for quantitative and qualitative evaluation of the modeling units (objects) by enabling 3D virtual models of the structures that cannot otherwise be seen, or seen in sufficient detail. As a proof of concept, simulation of the X-ray Log Scanners based on the parameterization of the CT is very promising as a suitable technique for imaging internal features in green subalpine fir logs. Due to limited sample size used in this study, while the results of CTSTEM are currently not intended to be part of industrial applications, it is a demonstration research tool that can illustrate potential benefits of modeling and simulation, based on CT scan data, to the Canadian forest product industry. CTSTEM provides means towards better utilization of the non-traditional subalpine fir species, which is essential for successful sustainable forest management in B.C.
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1 Objectives

To develop a new subalpine fir stem model (CTSTEM) based on data acquired from non-destructive computed tomography (CT) scanner as a research tool that can measure and describe logs and stems by its properties.

To demonstrate feasibility of simulated X-ray Log Scanner signals for imaging type of logs and nature of internal defects.

2 Introduction

Subalpine fir (Abies lasiocarpa [Hook] Nutt) is one the most underutilized species in British Columbia (B.C.). It constitutes approximately 1.13 billion m$^3$ of standing tree volume, which is about 22% of the total softwood volume in B.C. and 45% and 36% of the standing volume in the Prince Rupert and Prince George forest regions of B.C., respectively (15). The main reason for its underutilization is the presence of wetwood in its stems. Wood products, particularly lumber, plywood, veneer as prime economic products harvested from these regions are most adversely affected by the “wetwood” associated processing problems occurring during drying, machining, finishing, gluing, which significantly reduce overall quality and value of subalpine fir lumber and veneer (4-15). As the handful of commercially valuable species that in many areas have been logged out, to sustain B.C. forests over the long term, multi-species including once underutilized or species considered to be “less reputable” need to be harvested without depleting any particular species. Especially, under the growing pressure from steadily rising timber costs and increasing competition from non-wood materials, it is therefore essential to enhance understanding of subalpine fir tree growth and internal stem properties for integration of it into processes with optimal utilization (1-3, 68).

Scientific modelling and visualization of multi-dimensional images has revolutionized understanding structural and functional information of natural and man-made materials from various non-destructive imaging modalities providing a synergistic analysis capability for quantitative and qualitative evaluation of their internal objects. Scientific modeling and visualization uses advanced animation, simulation, and sophisticated computer graphics creating three-dimensional (3D) virtual models of materials assuring high accuracy of measurements, detection of internal external structures, and assessments of their shapes (65-68, 72-73). A three dimensional (3D) modelling and visualization of the internal structure details of tree stems based on the modeling and visualization principles would enable the same synergistic analysis capability for quantitative and qualitative evaluation of log/stem properties for optimal utilization of particularly underutilized less reputable species.

In recent years, to enhance understanding and prediction of tree growth, many different mathematical and simulation models have been developed for some commercially valuable tree species (69,70). These models can be classified into three main groups: functional, structural, and functional-structural. Functional or process-based models were developed to treat metabolic processes in considerable detail but simplify structure and structural dynamics to the level of caricature. While structural or morphological models describe tree architecture very realistically they pay little or no attention to growth processes. Although, a functional-structural model which combines the both in one modelling framework with a three-dimensional (3D) description of the tree crown, it only represents a tree using four modelling units.
(tree segments, tree axes, branching points and buds) with little regard to their interactions with internal structures of the stems. Underutilized tree species, such as subalpine fir with abnormal internal characteristics (such as wetwood), have never been the subject of any of these models.

Wetwood is a phenomenon known as areas of abnormal moisture content (water-soaked condition) in many species including subalpine fir. Based on the previous studies (4-15,68), wetwood zones can occur exclusively in the sapwood or in the heartwood but often a single wetwood zone can extent into both sapwood and heartwood. Although considerable progress has been made in qualitative and quantitative understanding of wetwood based on destructive (flitching) method, a synergistic three dimensional (3D) analysis for its quantitative and qualitative evaluation is still lacking. One important reason for this limitation has been a great difficulty in obtaining and hence manipulating accurate internal information on internal positions of wetwood. Existing technologies by external tree stem inspection have reached the point that little further progress is expected. With respect to visual inspections, even today’s most experienced sawyers cannot glean from an external inspection of the log its internal features and their location to any degree of accuracy. Therefore, for obtaining the internal information for effective and efficient utilization of subalpine fir stems/logs, two main needs must be satisfied.

First, a three 3D model of the subalpine fir tree, as a tool that can accurately describe and measure every log and stem by its internal and external properties for research purposes, needs to be developed. To overcome the above measurement constraints for detailed calculations of the internal properties of individual logs/stems, the model tree must be based on directly detail measurements obtained from a non-destructive method. Nondestructive measurements of inner properties of logs can be measured by various methods (17-64). For research purposes, X-ray computed tomography (CT) has been the most successful viable method to acquire cross-sectional (2D) images of logs.

Although the CT scanners provide useful information about internal structures of logs for modelling purposes, the conventional CT-scanning is currently too slow (<0.1m/s) for industrial on-line applications. In order to increase the scanning speed, different designs have been suggested. Gupta et al (75) suggested tangential scanning at speeds comparable with industrial processing of hardwood logs. Magnusson et al (76) showed that it should be possible to scan logs at 5m/s using a cone beam (2D-detector) and helical source path (spiral scanning). However, much work still needs to be done to develop large 2D-detectors and reconstruction algorithms. So far, the most successful method of measuring internal properties of logs at high speed on-line applications in sawmills have been to use two-fixed gamma or three fixed X-ray sources Log Scanners (62-64, 73). These Log Scanners have proven to be able measure important properties with acceptable levels of speed (2-3m/s) and accuracy for studied European species. To be able to promote usefulness of such technologies in Canadian wood products industry, it is necessary to have knowledge of their feasibility for measuring properties of saw logs from Canadian species such as subalpine fir with more complex and unique internal characteristics.

Consequently, the second need for efficient utilization of subalpine fir trees is to assess feasibility of integrating the new equipment, as a proof of concept, for imaging the type and the interiors of logs.

This report first describes the design and implementation of a surface-volume integrated tree stem modeling approach and X-ray log simulation techniques, called CTSTEM, aiming at meeting these needs; and subsequently related experimental results presented.
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4 Materials and Methods

4.1 Tree Selection

A total of 3 sample trees (total 9 logs, each 5m in length less than 90 years old in age) were sampled from subalpine fir natural stands in northern Kamloops region, B.C. Related tree and site information were recorded (Appendix I). Previously existing a total of 6 subalpine fir tree CT data (9 logs from three trees, age less than 90 and 9 logs from another trees age larger than 90 years old) data from Forts St James, B.C. Canfor Woodland were also used.

4.2 CT Scanning of Logs

Each log from each tree was scanned by an industrial computed tomography (CT) to obtain 2-D images of the logs at the Forintek/UNBC CT imaging Centre in Vancouver. A graphical representation of geometric design of the CT scanner appears in Figure 1a and the installed actual apparatus in Figure 1b. This full-size research apparatus is capable of collecting data from logs up to 100cm in diameter and 5m in length (with a spatial pixel resolution 0.65mm). This CT scanner is designed to scan a log in a vertical direction, unlike medical scanners that are configured to scan the human body by moving it along a horizontal axis. This includes a mechanical gantry with simultaneous translation and rotation of the log, a 512 channel detector array, a 3.5 MeV X-ray generation system, fan beam X-ray collimation, and data collection software. The 3.5MeV X-ray tube is mounted on one side of the apparatus and the detector array on the other side. The X-ray tube head is surrounded by a 10cm-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 radiation. The detector array is also surrounded by 7.5cm-thick lead shielding. 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. The detectors are modular. 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 (A/D conversion done with 18 bit A/D, the images has 16 bit grayscale resolution). Individual detector modules are laid side by side (currently 1.3mm apart) to create a large linear array for industrial applications. The two dimensional (2-D) imaging method used in this study is based on the bio-imagining research (BIR)’s ACTIS® 1000/3000 CT/DR imaging system.
4.3 3-D Modelling and Visualization of Stems

The modeling approach consists of three principal modules: (1) Preprocessing and segmentation of individual 2D CT image slices; (2) Detection and classification of internal wetwood and knots in the individual 2D CT image slices; (3) 3-D reconstruction and visualization of the internal features of the log. Figure 2 depicts the overall structure of the system. Figure 3 depicts a detailed flowchart describing the various components within the three modules.

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**Figure 1:** Graphical illustration of the geometric design of the industrial CT scanner

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a) 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.

b) showing the actual CT scanner installed at Forintek Canada Corp.
In the initial stages, the feature detection and classification procedure adopts a bottom-up processing approach. First, it processes and analyzes each CT image individually and then correlates the results from each CT image with those from neighboring CT images to extract and classify the relevant 3D defects. The knowledge of the 3D internal defects and the pattern structures deduced from the individual CT image slices of subalpine fir logs and results of an earlier destructive based study done by Forintek (69) logs is used for conceptualization of the reconstruction the 3D model of the internal defects and the log. As depicted (based on 17) in Figure 3, the reconstructed 3D model is used to detect and rectify errors in the segmentation and classification of the defects (wetwood and knots) in the 2D CT image slices.
4.3.1 Segmentation of a single CT image

The pixel gray level in a CT image represents the X-ray attenuation coefficient (which is proportional to the amount of X-ray energy absorbed). Figure 4 shows sample cross-sectional CT images of logs from the subalpine fir species. Lower material density results in lower gray-level pixel values in the CT image and vice versa. The density of the wood within a cross section of a log of the given species exhibits a significant variation depending on the growth ring structure and the presence of certain defects such as wetwood and knots within a given log. Figure 5 show the gray-level profile along a horizontal line.
passing through the center of the CT image—the gray-level variation caused by the ring structure in subalpine fir.

(a) sapwood and heartwood
(b) sapwood, heartwood, wetwood and knots
(c) sawwood, heartwood, and wetwood

Figure 4: Sample cross-sectional CT images of logs from the subalpine fir species

4.3.2 Gray-level variation in CT images

The significant gray-level variations observed in a CT image slice that is free of defects could be attributed to the following elements of wood.

4.3.2.1 Ring structure
The ring structure is composed of alternating layers of latewood and earlywood. Since latewood is composed of smaller size cells it has a higher density than earlywood and appears brighter in the CT images.

4.3.2.2 Sapwood and heartwood
In subalpine fir species, sapwood has higher density than heartwood because of higher moisture content. Since water has a higher material density than wood, regions of high moisture content appear brighter in the CT image.

(a) A portion of the CT image
(b) The gray level profile along a horizontal line passing through the center

Figure 5: Gray level variation due to the ring structure, sapwood and bark in the sample CT image of subalpine fir.
4.3.2.3 Knots
A knot is the portion of a branch that is embedded in the wood of a tree trunk. Knots tend to distort the normal growth rings in the tree trunk. Due to the higher density of cells within a knot, it is characterized by high gray-levels in the CT image. Most knots have an elliptical cross section.

4.3.2.4 Wetwood (wet pockets)
Wetwood is a result of high concentration of water in certain regions of the heartwood of the tree trunk. Wetwood or wet pockets are characterized by high material density and therefore exhibit high gray-levels in the CT image. Wetwood seems to have water content similar to the sapwood.

4.3.3 Histogram-based thresholding of CT image slices
Based on the characteristics of the wood structure and defects discussed and our earlier empirical observations (68), a CT image of a log cross section to be typically composed of four groups of gray-level intensity values. From the lowest to the highest gray-level value they correspond to pixels from (1) heartwood, (2) sapwood and wetwood, (3) knots, and (4) knots masked with wet-wood. Note that gray-levels from each of these classes could overlap with those of adjacent classes. Therefore, a combination of multiple-thresholding and area-based thresholding algorithms (17,19,32,57,61) were used for segmenting the CT image into the four classes.

4.3.4 Smoothing of the CT image
The CT image of a log contains a fair number of gray-level transitions among earlywood, latewood, and knots. However, since CT scanner’s spatial resolution is limited (CT scanner used in this study has 0.65×0.65 mm), a single pixel in the CT image may actually include wood elements from two or more classes, but may only be assigned a gray-level corresponding to a single class. Sometimes a small portion of wood may have abnormal density or may be assigned an incorrect gray value by the scanner (these pixels are termed as noisy pixels). If the thresholds selected above are directly applied to the raw CT image, one may experience the problem of over-segmentation and/or under-segmentation. In an over-segmented image a connected group of pixels arising from a single wood structure may be split into more than one region. In an under-segmented image pixels belonging to distinct wood elements may be incorrectly merged into a single region. This could result in false classification of normal pixels as defects and also failure to detect certain defects. It is therefore necessary to smooth the CT image to avoid problems of under/over-segmentation. Our selective smoothing algorithm designed for this purpose was based on (17) worked well for the purpose of detecting knots and wetwood.

4.3.5 Extraction of defect-like regions from a segmented CT image
After the three thresholds determined in Section 4.3.3 are applied to the smoothed image of Section 4.3.4, the image is segmented into four classes: 1) air; 2) entirely clear wood (sapwood and heartwood), 3) wetwood; and 4) knots.

4.3.5.1 Locating the pith
The physical pith is a small area which may be viewed as the biological center of a tree although it is rarely located in the geometric center of the log cross sections. It has an important role in aiding the identification of various wood features. For example, growth rings typically form a circular pattern with the pith at the center, and the longitudinal axes of knots normally pass through the pith. Assuming that
the pith is the innermost portion of the growth rings and that the growth rings are nearly circular in shape, a simple algorithm for locating the pith was designed. Our algorithm locates the pith using the Hough transform [17, (Fig. 6)] for circle detection. First, the Canny (20) edge operator in Matlab is applied to the raw CT image and the output thresholded based on edge strength. An edge map denoting the locations of the edge pixels and a gradient direction image are then obtained from the thresholded output. For almost all of the CT images, the pith is localized within a precision of approximately 15 pixels (9.6 mm).

![Figure 6: The Hough transform procedure for locating the pith (17).](image)

### 4.3.5.2 Identification of defect-like regions

Using a region-growing process (17), 8-connected pixels (i.e., indirect neighbors and direct neighbors) in the image belonging to the first class are grouped in the same region, whereas 8-connected pixels belonging to the fourth class are grouped in the same region. For each region obtained from the region-growing process, the following features are computed: region perimeter, region area, the region centroid, region slenderness, the maximum and minimum moments of inertia, and the region orientation, which is the direction of axis of least moment of inertia with respect to the x axis.

In order to optimize the feature extraction process, a minimum-area criterion was first used to decide whether a region should be retained for further processing or deleted from the region list in accordance with the flowchart given by Figures 2 and 3. For each retained region, the orientations of its major and minor axes are computed as described above. The region’s slenderness is used to further classify the defect-like regions (wetwood and knots) from the second-class regions. Over the course of several experiments we have empirically determined the slenderness values for wetwood and knots from several CT images. The contour of the regions is then simply represented by the convex hull or a polygon for knots and wetwood.

### 4.3.6 3-D Analysis of defect-like regions across CT image slices

The ultimate objective is to detect 3D log defects (wetwood and knots) from a series of CT images. Therefore, we need to reconstruct and model the 3D defects from the 2D defect-like regions and also verify if they indeed constitute a valid class of the defects. Since a log is from a living tree, the physical condition as well as the biological characteristics of the tree may result in a large variation in the CT images of a log. A region in a segmented CT image may be inferred as belonging to a defect, but in reality may be caused by a variation in the physical condition in the wood. For example, in the CT image of subalpine fir, a 2D region corresponding to the bright regions in the heartwood is caused by high local wetwood (a moisture pocket), can be incorrectly classified as a knot-like region by the 2D analysis procedure alone as described in the previous section.
This example re-emphasizes why it is necessary to classify 2D defect-like regions if they have no appropriate 3D support in neighboring CT images to constitute a valid 3D defect. Even if a defect-like region has 3D support from neighboring CT images, the defect-like region and the corresponding defect-like regions in neighboring CT images are considered to constitute a false defect if they do not satisfy the 3D parameters of appropriate valid defect. In fact, by using knowledge derived from previous experiences from non-destructive testing based study (68), most ambiguities that arise in the segmentation and classification of defects in 2D CT images were resolved via suitable conceptualization (grouping) of 3D analysis of defect-like regions across successive CT image slices (next section).

4.3.7 Preliminary grouping of defect-like regions

To implement the 3D modeling and analysis, preliminary groups of defect-like regions are generated from the defect-like regions list using an iterative clustering procedure with the geometric parameters (based on 26, 30, and 68) as depicted in Figure 7. The parameters $r$ and $w$ denote the distance of the centroid of the defect-like region from the pith, whereas $Q_{\text{min}}$ denotes the region orientation. Each group is essentially a series of defect-like regions with identical class labels that are spatially connected across CT image slices. A group may be classified as a valid defect if it satisfies a series of 3D tests. In order to optimize the 3D analysis, a group is rejected if the number of 2D regions within it is less than a pre-defined threshold. The threshold values are dependent on the minimum size of the defect to be detected and the error tolerance in the pith location.

![Figure 7](image)

**Figure 7:** Proposed geometric parameters used to group defect-like regions (b); representation of knots (a), representation of wetwood in accordance with (b).

4.4 3-D Reconstruction and Visualization: Surface-Volume Integrated Model

Volume rendering (VR) is a direct representation of a three-dimensional data set. Unlike surface rendering, this technique does not require a prior knowledge of the surface for intermediate generation of geometrical representation. A geometric approximation of a surface within a volume set is formed from a cross connection of data points of equal value or density specified by a threshold value (65-68). Volume rendering does not use geometric representation of the volumetric data, thereby including all the data points in the volume. Such an approach significantly reduces the number of falsely identified surfaces.
characteristic from surface based methods resulting from hard decisions about the inclusion of boundary voxels in noisy or poorly defined features using a form of thresholding. The rendering is done from back to front by ray casting, and each voxel is blended with the previously drawn voxel using transparency. The transparency is calculated by interpolating the individual intensities of the voxels along the line of sight. The opacity of voxel $k$ is:

$$O_k = \frac{I_k - I_{k-1}}{I_{k+1} - I_{k-1}}$$

where $I_{k-1}$ and $I_{k+1}$ are the intensities of the voxels in front of and behind the $k^{th}$ voxel respectively. Voxels in the back of the volume are partly obscured by voxels in front. If the opacity for a voxel is zero, that voxel becomes transparent and contributes nothing to the intensity; when $O_k$ is 1, the voxel is opaque and transmits no light.

A current drawback of volume rendering techniques is that a large amount of data, which has to be handled does not allow real time applications for visualization (65-68). Also, manipulating and analysis processes demand polygonal representation of the object to perform these tasks in an intuitive and friendly way. Furthermore, a complete framework for visualization and manipulation of volume data demands the integration in the system of some non-volumetric objects. In order to profit from the superiority in visualization of the VR techniques and the versatility for interaction and manipulation tasks of the surface (S) rendering approach, a surface/volume integrated (SVR) model must be defined. Thus, in order to profit the potential of the (SVR) as an intermediate model for surface rendering, an enhanced version has been created, incorporating the volumetric (data conversion based) information required to achieve a cogent direct volume visualization. Based on the concepts of (65-68), the integrated SVR model and its implementation strategies were developed using the proposed SVR-based integrated model (Figure 8). The data conversion based volume rendering is based on converting polygonal model and volume data into a common codification scheme, so data conversion techniques have to be applied to reduce either surface to volume data through scan-conversion techniques or volume data to surface representation through a mapping strategy to extract the iso-surface fitted into the volume.

![Proposed iso-surface/volume integrated model by data conversion approach](image)
Based on the principles in (65-68 and the proposed Figure 8), the 3D reconstruction (modelling) and visualization has two modes: (i) the natural mode where the log is viewed as a solid entity. This mode allows one to examine the external features of the log in opaque form; (ii) the defect mode where the defects within the log are viewed as solid entities and the rest of log is viewed as a semi-transparent entity. This viewing mode is used to highlight the internal 3D defects in the log and also view the relative 3D positions of these defects within the log or stem. In both modes, the user can manipulate the log via translation and rotation in a world coordinate reference frame, via rotation about the log axis and by changing the viewpoint of observation in a 3D coordinate reference frame or in the log coordinate reference frame.

Our model based surface and volumetric (voxel) modelling primitives is conceptually different in contrast to other log models and its internal modeling primitives (such as wire frame models). Our approach generates a 3D volumetric log model derived by the stacking of the data and results derived from successive CT images. Consequently, the results of our simulation and visualization algorithms are more realistic. The graphics in our model is designed to be interactive, flexible and uses a layered object-oriented model development methodology. The 3D renderer consists of procedures for setting up the 3D transformations, projections and other viewing parameters. The object layer consists of (i) high-level objects such as the 3D log and 3D defect, (ii) low-level objects describing the volumetric model, surface model and cross sectional boundary of the log, and (iii) raw data which consists of the CT image slices, cutting plane data and cutting line data. The data store layer consists of a file system that stores all the raw data.

4.5 Measurement of 3D Wetwood and Knot Parameters Using the 3D Model

A knot is a section of branch that is embedded in the wood of a tree trunk. The knot angle is referred as the angle between the branch pith axis and the x-axis. The angle, measured between the log x-axis and the line passing through the centers of the 2D knot-like regions in successive CT image slices, was the most important factor in distinguishing a knot from another feature and the wetwood class (Figure 7c).

Other relatively more important 3D measurements to distinguish knots from wet pockets include the change in region area across successive CT image slices, and the region shape. For a normal knot, the area should change from small to large to small along successive CT slices containing the knot, and the region shape is oval with a different slenderness factor. For moisture pockets, there is more irregular change in region area and the region shape has different and highly variable slenderness and orientation factor in a given range. For defect group classes, a 3D orientation measurement and the measurement of the angle between the log pith axis and the line passing through the region centers in successive CT image slices are also used to determine the validity of the group.

4.6 Experimental Validation of Defect Identification and Localization Procedures

The procedures for defect identification and localization were subject to an experimental validation. Based on the 3D visualization of each scanned log, two logs from the trees best representative of a high incidence of internal defects (wetwood and knots) was selected in the validation process. Sections of the first log were physically cut at across sectional locations where the corresponding CT images were registered. The cross sections of the cut logs were imaged with a digital camera with 24-bit color resolution (i.e., 8 bits each for red, green and blue) and spatial resolution of 100 pixels per linear inch. The defects in the color image were manually identified and treated as solid (baseline) truth for the purpose of validation. The corresponding registered CT images and that of color images were
comparatively used for the purpose of validation. A verification test was performed to ascertain whether a defect-like region in the CT image had a corresponding region in the color image and vice versa. The stacks of the registered original CT-images were carefully inspected and all knots and wetwood with a diameter larger than 8 mm were manually marked. The reason for this limit was that smaller knots and wet-wood are not taken into account for the comparison. The original and reconstructed CT-images were then compared, and for every marked knot in an original image, the presence of a corresponding knot and wetwood was checked in the reconstructed image. The boundary detected in the reconstructed image was projected back to the original image. A further comparison among the digital camera based cross section, corresponding CT image and detected knot and wetwood was also made. Furthermore, a correspondence between two defect-like regions was assumed to be established if (i) the defect-like regions have identical labels (knot or moisture pocket), (ii) the displacement of the region centroids in the two images was less than a pre-defined threshold, (iii) the difference in region orientation was less than a pre-defined threshold and (iv) the overlap factor defined as the ratio of the area of intersection of the two regions to the area of the region as measured in the color image was greater than a pre-defined threshold. This comparison of presence of knot or wetwood and mapping the boundaries back on the original image and the localization accuracy gives a measure of the accuracy of knot detection and wetwood. A further verification of wetwood and knot dimensions was based on manual measurements of their properties on sawn (by a Wood Mizer) 25 mm-thick boards from the second log.

4.7 Simulation of the X-Ray Log Scanner

The part of the study is based on a total number of 6 subalpine fir logs from a Kamloops region in B.C. All logs were computed tomography (CT) scanned using Forintek’s industrial CT scanner located in the Vancouver Lab. The CT images were used as baseline data to simulate the industrial X-ray scanners. Computer algorithms were developed to obtain simulation of signals for the two fixed (a) and three fixed (b), and cone-beam (c) source X-ray Log Scanners (Figure 9) based on the publications (58-64) by modifying function from signal and image analysis tool boxes in Matlab 6.5.1. The beams were assumed to be perpendicular to the feeding direction of logs. The simulated signals from parameterization of CT images were compiled into images reconstructing (producing) two X-ray plates. The simulated images consisted of one row of pixels for every 10mm of the log length, which is the same as one row for every CT image.

Figure 9: Schematic description of two and three-fixed X-ray fan-beam log scanner (60, 66,77)

For validation purpose, two center-boards from the second log were visually graded in green condition by an experienced grader. Frame by frame, the full length cross sections of the two center boards were imaged with a digital camera with 24-bit color resolution (i.e., 8 bits each for red, green and blue) and spatial resolution of 100 pixels per linear inch. A color-based digital surface reconstruction of the boards
was done in Photoshop software. The defects in the color surface image were visually identified and treated as solid truth for the purpose of validation. The counterfeit board surfaces were also produced by a simulated sawing of the reconstructed 3-D CT log. A visual assessment test was performed by an experienced grader to ascertain whether a defect-like region in the simulated X-ray image had a corresponding region in the actual board surface, the color based board surface image, that of CT surface, digital radiography (DR) images, and vice versa.

The two and three source X-ray Log Scanner make it possible to image logs that may enable sorting of the logs according to quality properties but does not make it possible to measure detailed information of individual internal structures such as knots or wetwood. In order to overcome this limitation, using the three fixed-point X-ray images, a method (called sector oriented reconstruction technique-SORT) was applied for computing properties of knot clusters (60). The name refers to the principle of applying a cylindrical co-ordinate system with discrete sectors and slices. The object space is composed of volume elements with dimensions far larger than imaging pixel size. The densities of the volume elements are estimated to recognize potential knot locations and sizes. The method uses prior knowledge of typical shapes and densities of knots and stems, along with evidential reasoning when looking for candidate knot directions. The method produces an estimate of knot characteristics at two levels: (1) volumes and co-ordinates of knot clusters, and (2) thickness, lengths, volumes, and co-ordinates of individual knots. In some cases, the information from three projections is not enough to separate out individual knots. A confidence index is therefore calculated to indicate the reliability of the results. The performance of the detection algorithms was demonstrated with data from simulated logs.

For cone beam simulation, approximately 1m long parts of one of the selected subalpine fir log CT data was used. The log part was originally scanned in every 10mm with the scanner. Then volume covering one whorl from log section was chosen for the simulation. These volumes were used as an input data when simulating a cone beam scanner as described by Magnussen Seger and and Danielson (75). The scanner was simulated with 33 detectors in each direction. The segmentation algorithm as described in Grundeberg and Grondlund (77) were then applied on both the original CT data and the cone beam volumes. The shape of the cross section, the border between heartwood and sapwood and pith was measured in the CT data and this information was used when the segmentation algorithm was applied to the cone beam volumes. The segmentation algorithm was integrated with iso-surface extraction producing an individual parameter description of every detected knot and wetwood. The computation of the simulations was done using Matlab 6.5.1 Image and Signal Processing Toolboxes.

5 Results and Discussion

In the following section, we present experimental results using the developed model.

5.1 3-D Modelling and Visualization of Subalpine fir stem

As mentioned earlier, our model is capable of 3D reconstruction and visualization of the scanned logs stems based on the integrated surface/volumetric modeling modes (primitives) in contrast to other log models (such as wire frame models). In both modes, the user can manipulate the sections of a log, a full log, or stem via translation and rotation in a coordinate reference frame, via rotation about the axis and by changing the viewpoint of observation in a coordinate reference frame or in the coordinate reference frame. The modeling and visualization results of the selected wetwood, knot (whorl) and both wetwood
and knot are shown in Figure 10 in the defect volume mode where the sections are viewed as semi-transparent entities. The 3D modeling and visualization of stems in iso-surface mode showed that there are two main patterns of occurrence in radial and longitudinal locations within the scanned trees. The first pattern found consists of portions of regions mostly occurring in close proximity to inner heartwood near the pith of the tree stems. In this report, this type of wet-wood is referred as a wet-pocket (Figure 11b). The second pattern found consists of streaks of wet-wood generally confined to the outer heartwood in very close proximity to the heartwood-sapwood transition zones of the sample tree stems. In this report, this type of wet-wood is referred as wet-streak (Figure 11a). The frequency of the spatial occurrences of the wet-wood type seems to be irregular. The modeling and visualization results of the selected logs are shown in Figure 12 in the volume mode (Figure 12a, c) and as iso-surface entities (Figure 12b,d). Figure 13 shows a virtual 3D model of a subalpine fir stem with branch segments in second and third logs.

![Figure 10: 3-D volume rendering and visualization of the segments of detected internal defects in a log: wetwood; knots (b), wetwood and knots(c)](image)

![Figure 11: 3D iso-surface rendering and visualization of the segments of detected internal defects in a log (CT slice No 297-411): wetwood; knots (b), wetwood and knots(c).](image)
Modelling of Subalpine Fir Tree Stems Using Industrial Computed Tomography (CT) Imaging and Simulated X-Ray Scanning

Figure 12: 3-D rendering and visualization of the logs in both volume and isosurface modes.
Figure 13: 3D virtual model of a subalpine fir tree consisting of butt, mid and top log.
5.2 Measurement of 3D Wetwood and Knot Parameters Using the 3D Model

Table 1 shows the properties of knots encountered in several CT images derived from one of the subalpine fir stems. Table 2 shows the wetwood values encountered in the sample CT images. Table 3 summarizes variation of volume by feature within one of the subalpine fir stems.

Table 1: Angle, length, and size for knots along the sample tree stem by CTSTEM

<table>
<thead>
<tr>
<th>Vertical distance of pith from base (mm)</th>
<th>CT image number at the pith</th>
<th>Knot Length (mm)</th>
<th>Angle (degree)</th>
<th>Size (mm)</th>
</tr>
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<tr>
<td>251</td>
<td>25</td>
<td>170</td>
<td>-39</td>
<td>59</td>
</tr>
<tr>
<td>575.5</td>
<td>58</td>
<td>182</td>
<td>-34</td>
<td>31</td>
</tr>
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<td>715</td>
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<td>852</td>
<td>85</td>
<td>167.1</td>
<td>-30</td>
<td>39.9</td>
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<td>149.8</td>
<td>-18</td>
<td>41</td>
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<td>116.4</td>
<td>137.8</td>
<td>-6</td>
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<td>133.7</td>
<td>-19</td>
<td>33.9</td>
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<td>1832</td>
<td>183.2</td>
<td>145.9</td>
<td>17</td>
<td>22.6</td>
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<td>183.2</td>
<td>116</td>
<td>2</td>
<td>17.2</td>
</tr>
<tr>
<td>2041</td>
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<td>93.3</td>
<td>14</td>
<td>9.9</td>
</tr>
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<td>-8</td>
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<td>30.4</td>
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<td>368</td>
<td>152.7</td>
<td>11</td>
<td>55</td>
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<td>4196</td>
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<td>36</td>
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<td>4524</td>
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<td>130.3</td>
<td>3</td>
<td>30.4</td>
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<td>12</td>
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<td>545.6</td>
<td>126.1</td>
<td>4</td>
<td>22.6</td>
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<td>557.6</td>
<td>110</td>
<td>19</td>
<td>44</td>
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<td>120.3</td>
<td>11</td>
<td>28.2</td>
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<td>89.1</td>
<td>-16</td>
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<td>110.3</td>
<td>16</td>
<td>24</td>
</tr>
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<td>6474</td>
<td>689.0667</td>
<td>118.3</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>6912</td>
<td>762.0667</td>
<td>111.6</td>
<td>16</td>
<td>28.2</td>
</tr>
<tr>
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<td>762.0667</td>
<td>103.4</td>
<td>10</td>
<td>26.1</td>
</tr>
<tr>
<td>7627</td>
<td>881.2333</td>
<td>114.4</td>
<td>6</td>
<td>20.5</td>
</tr>
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<td>881.2333</td>
<td>93.4</td>
<td>14</td>
<td>24.7</td>
</tr>
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<td>8223</td>
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<td>-3</td>
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<td>8384</td>
<td>1007.4</td>
<td>106.4</td>
<td>17</td>
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<td>1007.4</td>
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<td>5</td>
<td>30.4</td>
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<td>8652</td>
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<td>83.8</td>
<td>14</td>
<td>24.7</td>
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<tr>
<td>9100</td>
<td>1126.733</td>
<td>100.7</td>
<td>23</td>
<td>26.1</td>
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<td>9100</td>
<td>1126.733</td>
<td>90.8</td>
<td>8</td>
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<td>9501</td>
<td>1193.567</td>
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<td>8</td>
<td>19</td>
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<td>9560</td>
<td>1203.4</td>
<td>81.8</td>
<td>-6</td>
<td>17</td>
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</tbody>
</table>
Table 2: Example results of measurement of wetwood properties by CTSTEM

<table>
<thead>
<tr>
<th>CT Slice No (297-411)</th>
<th>CT image slice no.</th>
<th>Distance of centroid from the pith</th>
<th>Vertical length (mm)</th>
<th>Horizontal Maximum length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOG1</td>
<td>397–411</td>
<td>56.704</td>
<td>314.64</td>
<td>288.64</td>
</tr>
<tr>
<td>LOG2</td>
<td>397–411</td>
<td>12</td>
<td>44.1</td>
<td>45.3</td>
</tr>
<tr>
<td>LOG3</td>
<td>397–411</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: Example volume (in $m^3$) calculations of the stem features by CTSTEM.

<table>
<thead>
<tr>
<th>CT slice No</th>
<th>Wetwood</th>
<th>Heartwood</th>
<th>Sapwood</th>
<th>Total Knot</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-99</td>
<td>0.001417</td>
<td>0.04571911</td>
<td>0.02373209</td>
<td>0.001416</td>
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<tr>
<td>100-199</td>
<td>0.000131</td>
<td>0.04126757</td>
<td>0.02430127</td>
<td>0.001595</td>
</tr>
<tr>
<td>200-299</td>
<td>0.000982</td>
<td>0.04668576</td>
<td>0.02382522</td>
<td>0.000932</td>
</tr>
<tr>
<td>300-403</td>
<td>0.000631</td>
<td>0.04901418</td>
<td>0.02330185</td>
<td>0.001732</td>
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<tr>
<td>404-499</td>
<td>0.005499</td>
<td>0.03932908</td>
<td>0.02066396</td>
<td>0.001923</td>
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<tr>
<td>500-599</td>
<td>0.005199</td>
<td>0.03309994</td>
<td>0.01919903</td>
<td>0.001081</td>
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<tr>
<td>600-699</td>
<td>0.003307</td>
<td>0.03406293</td>
<td>0.01964822</td>
<td>0.001674</td>
</tr>
<tr>
<td>700-799</td>
<td>8.03E-05</td>
<td>0.02177558</td>
<td>0.01955233</td>
<td>0.004741</td>
</tr>
<tr>
<td>800-899</td>
<td>1.14E-05</td>
<td>0.02150472</td>
<td>0.01535299</td>
<td>0.000569</td>
</tr>
<tr>
<td>900-999</td>
<td>1.34E-05</td>
<td>0.01638597</td>
<td>0.01648892</td>
<td>0.000184</td>
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<tr>
<td>1000-1099</td>
<td>2.15E-05</td>
<td>0.01508481</td>
<td>0.01094825</td>
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<td>1099-1199</td>
<td>1.34E-05</td>
<td>0.01386786</td>
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<td>1199-1299</td>
<td>4.39E-05</td>
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<td>1299-1399</td>
<td>3.27E-05</td>
<td>0.00802771</td>
<td>0.00970112</td>
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</tr>
</tbody>
</table>

As a general trend, butt logs seem to have slightly higher average wetwood volumes than mid and top logs with irregular wetwood shape and pattern distribution (Table 4). The irregular formation of wetwood with no obvious evidence of association with knot types (particularly dead or partially dead knots) on contrary having a presence with full attached green branches may be explained by the concept of compartmentalization and barrier zone formation: is a boundary-setting defense process. The results indicated a trend linking wet-wood patterns to tree age and diameter: while in general, larger-diameter and older trees contained relatively more wet-wood than smaller and younger trees; large diameter trees also contained relatively more wet-wood than approximately similar age but with smaller diameter trees (Table 4). The objective of this study was not develop a statistical model to analyze variation of wetwood within stem and among stems. However, establishing such statistical models using data obtained by CTSTEM is essential second phase to this study. To establish possible statistical relations between wetwood and other tree properties (such as stem location, knot types) and forest site characteristics, additional tree samples (at least 6 from each site) from various sites must be evaluated using the model.
Table 4: Trend of variation of average wetwood and knot volume (in m$^3$) with stem location, age and diameter.

<table>
<thead>
<tr>
<th>Tree (T) and Log ID (Tree Site)</th>
<th>Age (years)</th>
<th>DBH (cm)</th>
<th>Tree height (m)</th>
<th>Knot volume</th>
<th>Wetwood volume</th>
<th>Log volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1_butt_log (Forth St John)</td>
<td>157</td>
<td>39.7</td>
<td>23.7</td>
<td>0.00056</td>
<td>0.00281</td>
<td>0.6286</td>
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<tr>
<td>T1_mid_log (Forth St John)</td>
<td>157</td>
<td>39.7</td>
<td>23.7</td>
<td>0.00042</td>
<td>0.00174</td>
<td>0.3032</td>
</tr>
<tr>
<td>T1_top_log (Forth St John)</td>
<td>157</td>
<td>39.7</td>
<td>23.7</td>
<td>0.00006</td>
<td>0.00075</td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>0.00530</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2_butt_log (Forth St John)</td>
<td>117</td>
<td>42.4</td>
<td>28.8</td>
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<tr>
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<tr>
<td>T3_butt_log (Forth St John)</td>
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5.3 Experimental Validation of Defect Identification and Localization Procedures

The stacks of original CT-images were carefully inspected and all knots and wetwood with a diameter larger than 8 mm were manually marked. The original and reconstructed CT-images were then compared, and for every marked knot in an original image, the presence of a corresponding knot and wetwood was checked in the reconstructed image. The boundary detected in the reconstructed image was projected back to the original image. A further comparison among the digital camera based cross section, corresponding CT image and detected knot and wetwood was also made. This comparisons of presence of knot or wetwood and mapping the boundaries back on the original image gave a measure of the accuracy of knot detection (Figures 14 and 15). One of the logs was measured for knot size detection accuracy on the center-sawn board. The pith side of every right center-board was then checked for knots with visible knots. Figure 16 shows an example of a digital surface of the sawn board where it is possible to measure knot length and size. For a total of these 37 knots in each board, the diameters of the corresponding knots were then measured on the boards and were compared to measurements made on the CT images. This comparison makes it possible to analyse the accuracy of the diameter measurements. The correlation between N>8 measured on real and reconstructed boards was relatively high, R$^2$ 0.796 (Figure 17).

![Figure 14: Validation of detection results by comparison to actual CT vs detected boundary: (a,d) original CT image with wetwood and knot; (b) detected wetwood, (c) mapping the boundary of the detected wetwood back on to original CT, (e) detected knots, (f) mapped knot boundary back on to the CT image.](image-url)
Figure 15: Validation of results by comparison between the color digital image

Figure 16: Example of a knot where it is possible to measure the diameter and length at a well defined position.

Figure 17: Measured number of knots larger than 8 mm counted on the sapwood side of the real centre boards as a function of predicted number of knots. The predicted number of knots is the number of knots larger than 4 mm counted on the sapwood side of the reconstructed boards.
An example of verification and localization accuracy of wetwood and knot in terms of the average centroid displacement, average region orientation difference is given in Table 4.

Table 5: Example of verification of detection of wetwood and knot with centroid analysis.

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5.4 Results of Simulation of X-Ray Log Scanners

As a proof of concept, our simulation of the two X-ray Log scanners based on the CT images of the limited number of logs showed that they can be used for separation of logs into groups, butt logs, intermediate logs, and top logs based on the information from the simulated signals (such as shape of a log, taper, butt taper, bumpiness, density level, and density variations; Figure 18). The images produced from the simulation of the signals also indicated that it is possible to image wetwood and knots within the logs (Figure 20). Therefore it may be possible to predict the grades of logs (Figure 19). Figure 20 presents a comparison of the experimental verification among the results of simulated signals of the X-ray log scanner, CT imaging, digital radiography and actual digital surface of the board. To fully explore and quantify the grading accuracy, sample size must be increased. Subsequently, to increase the confidence quantitatively, the results of large samples must be integrated with multiple regression statistical models.

Figure 21 (a-f) shows the enhancement procedure (based on 60) using the back projection of X-ray signals from the three fixed X-ray sources. The basic idea comes from computed tomography (CT) – radon transform principle, with the exception that only three projections are used. The number of projections cannot be much larger because of the speed of actual sawing process sets a tight limit for imaging time. The output of the computation of the three fixed x-ray simulation (a-f) for calculation of sizes of wetwood and knots is given in Figure 21 (g-j).

The computational results include a confidence figure indicating the reliability of the estimated knot and wetwood data. The confidence figure and cluster volume help to decide which level of information should be used in log sorting. However, the reconstruction from a small number of projections has inherent uncertainty. In the general case, an infinite number of solutions may be derived from the same projections. The possibility of finding a correct result is better in our application, where the object is fairly simple. The object can be modeled and constrained and can be set to guide the reconstruction process. In our application, uncertain information is combined to find probable knot and wetwood locations. In most cases this process is successful, but not always. For example knot and wetwood patterns produce different results when imaged from different directions. This is because the projection angles affect how the shadows of the real object are cast on the cross section, and how ghost images are generated. Because of density of a volume element cannot be determined reliable, quality grading of knots and thin wet-streaks are not possible.
Figure 18: Simulation result of X-ray Log Scanner for logs from logs different stem locations.
Figure 19: Experimental validation of the two fixed x-ray source signal simulation: actual board (d), corresponding counterpart CT image (b), digital radiography of the log (c), and simulated X-ray image of the log (a).
Figure 20: Simulated two-fixed source X-ray image enhancement (a) and detection of wetwood and knots (b) by a simple segmentation process.
Figure 21. Simulation of reconstructing, enhancing and detection from x-ray image from three-fixed source with angular filtering; and cone beam geometry: (a) cross-section backprojection from three projections. (b) cross-section after filtering with regard to polar angle, (c) image density averaged as function of angle, (d) weighted sum of (b) and (c), (e-f) the final image after thresholdings; (g-j) application of the steps (a-f) on a CT image. (i: detected knot, j: detected wetwood), (k) cone beam simulation (a: original CT image, b: slice generated based on 33 detector array and iso-x-ray detection (c-d) and reconstruction of the X-ray image (e)).
**5.5 Discussion**

This report describes the design and implementation of a new surface-volume integrated tree stem model, CTSTEM, for measuring and visualization of three-dimensional (3D) properties of subalpine fir stems from x-ray images of various projections. CTSTEM has two main components. Using full scale X-ray projection (CT) data, the first component of CTSTEM represents a subalpine fir tree stem using five modelling units, which closely resemble the real stem structure of the trees: shape, sapwood boundary, knots, branch segment, and wetwood. Design of this component consists of two primary phases. The first phase comprises the segmentation of a single CT image slice, which results in the extraction of 2D defect-like regions. The second phase comprises of the correlation of the 2D defect-like regions across CT image slices in order to establish three-dimensional (3D) support. The 2D defect-like regions with adequate 3D support are labeled as true defects. The 3D reconstruction and visualization of the modeling units is based on the volume-surface-integrated modeling concepts.

The second component of CTSTEM represents logs based on parameterization (simulation of signals) of the CT images. The basic idea is based on the principles of CT, with the exception that only three projections are used. The aim was to simulate principles of industrial X-ray Log Scanner based on three fixed X-ray sources. Using the simulated signals, the component creates x-ray images of logs and assesses the feasibility of using the X-ray Log Scanner to image internal properties of subalpine fir logs. Exact reconstructions of the internal object from the three projections were not possible. However, good estimates for the size and co-ordinates of the knot and wetwood patterns can be achieved with the method.

As resources become scarce, competition increases, and alternative materials continue to target markets historically dominated by wood, manufacturers of wood products must improve their production processes and must integrate alternative tree species to stay competitive. Increased efficiency, increased yield, and improved information exchanged through application of technology will become issues of growing importance throughout the industry. In the past, when confronted by similar challenges, it was feasible for the Canadian forest products industry to adapt one of two alternatives to relieve the immediate impact on the restrictions. Either it identified another species with similar characteristics that might be substituted in end-products, or it converted from all wood to a partial-wood-based-engineered-wood-products. However, in an increasingly complex and competitive future, the forest products industry will progressively be forced to turn to new technologies not only to improve utilization of declining wood supply but also to integrate trees in their process that have been underutilized species such as subalpine fir. Improved timber utilization of this species will depend upon a continually advancing scientific knowledge of basic research in its wood properties through innovative technologies.

This project presents research tools that addresses the critical barriers to improved wood utilization and that provides the scientific base from which new research and development can proceed. As proof of concepts, the major areas of focus include: (1) application and development of innovative scanning technologies such as CT and industrial X-ray scanning, and (2) development of modeling, visualization and simulation techniques. These tools will enable necessary innovative technology and related scientific information required to close the information gap to enhance optimize timber qualities to meet manufacturing needs from the subalpine fir species. Furthermore, utilization of North America’s first Industrial CT imaging lab. at Forintek and simulation of the X-ray scanners for their feasibility to be installed in B.C forest products industry meet directly the mission of Forest Science Program through boosting BC reputation in North America while creating new knowledge and technology in needed areas.

By using the developed 3D computer model utilizing the CT technology and simulating X-ray Log Scanner methods, a better understanding of branch geometry, knot, and wet-wood structures in the subalpine fir species is possible by extending its use to larger sample size and more sites. This output of
the model can have indirect implications for other species not only to help manage stands for high quality saw-logs, but also allow considering knots and wetwood at various stages of stem/log utilization for possibility of improving the value of wood products produced using equal or less forest assets and therefore improve estimates of sustainable timber production, reduce cost of timber production and as a result enhance the bottom-line results of sustainable forest management.

This model can be used for developing knowledge and decision making tools for development of wood quality integrated resource utilization and management other than existing volume based silvicultural systems to integrate and optimize production of timber /analytical and decision making models for assessment of timber resource. Therefore, it fits well with sustainable forest management objective of increasing value of output from the existing wood volume input.

Quantitative understanding wet-wood (a bacterial infection in subalpine fir) formation will provide possible knowledge for designing forest management that aims at improving forest health, growth yield and increase the production of high quality timber, which is essential for successful sustainable forest management. This may be linked with various molecular model technologies to assist in understanding gene flow, genetic improvements of the trees.

This project used a new technology (the CT) to simulate and develop a new technology (X-ray)-a technology with a difference. Historically, new traditional technologies offered the industry equipment that forestry and wood operations process raw material with higher volume using traditional resource standard. In the long run, successful sustainable forest management will depend on new technologies that can evaluate the forest value and increase the value of wood products produced using equal or less resource and therefore enhance the bottom-line results of sustainable forest management.

6 Conclusions and Management Implications

1) Computer Tomography scanning (CT) scanning is a powerful research tool for acquiring data for the modelling and visualization of different stem properties of subalpine fir species.

2) CTSTEM is capable of automatic detection, 3D modelling and visualization and calculation of parameters of subalpine fir stem modelling units (wetwood, sapwood boundary, knots, and branch segment).

3) As a proof of concept, simulation of the X-ray Log Scanners based on the parameterization of the CT is promising as a suitable technique for nondestructive imaging of internal features in subalpine fir green logs. It has been shown that it is possible to image and detect the wetwood and knots in subalpine fir logs.

The current version of CTSTEM does not perform well when CT images containing growth rings with irregular shapes (false rings), containing very dense annual rings due to scattered distribution of wetwood around the annual rings, where the width of the rings is not obvious, and with CT images that exhibit low-intensity variation between knots and masking wetwood. The low speed of calculations is also a issue. These problems need to be addressed in the future versions of the model. The segregation difficulty between knot and masking wetwood due to low intensity difference is the result of the existing
inefficiencies in the traditional image analysis methods. A possible integration of more advanced non-traditional image analysis methods in the modeling concepts can reduce the detection inaccuracy in the referred specific CT images. A use of more powerful computing hardware could make CTSTEM capable of effectively handling large data sets in a faster time needs to be explored. For a multi-faceted modelling of the trees, CTSTEM should be integrated with functional-structural tree model, which combines a process-based model with a three-dimensional (3D) description of the tree crown in one modelling framework.

Although not all physical features of the X-ray Log Scanners have been simulated, simulation of the X-ray Log Scanner signals using computer tomography (CT) images of subalpine fir species are promising such that the X-ray Log Scanner with two or three X-ray sources may have a great potential to become a powerful tool for control of the sawmill process of subalpine fir species. However, a lot of work remains to be done before the full potential of the scanner can be utilized. Due to the special features of wetwood, further image enhancement procedure and intermediate thresholding steps must be simulated to guarantee a more accurate detection of slimmer wetwood streaks. However, the importance of the simulation procedure here in the fact that knots and wetwood are visible in the simulated X-ray image; and enhancing the detection procedure can be done by going back to the underlying image data.

In the X-ray simulations, strong object details tend to hide weaker ones or their shadow combined into extra ghost details. However, utilizing knowledge of the properties of knots and stems we were able develop a method for determining the coarse shapes of the knots and wetwood. Very knotty (masked with wetwood patterns) logs are the most difficult to analyze. It would be valuable for log sorting to know the knot quality (fresh knot, dry, or dead). However, the density values determined from three projections are inaccurate, and thus the quality of individual knots cannot be accurately calculated. Cone-beam geometry based simulations show better accuracy in terms of imaging and detecting the features. The methods presented here are tuned to knot and wetwood patterns in the sampled logs, similar principles might be useful for other logs and stem but must be modified accordingly. We have concentrated on a limited number of samples only. The accuracy must be evaluated in large samples. Applying this to different samples with different distribution of knots and wetwood would require modifications. A new way of finding clusters and handling single knots must be developed. Also the stem density profile is different which affects the density parameters. Statistical models that predict the log grade based on variables measured by the X-ray Log Scanner need to be developed and calibrated using with larger log samples.

However, since the current study was based on a limited number of tree samples, the results of the components of CTSTEM must be extended to a larger sample size and a statistical analysis component must be integrated that predicts the stem and log grade of subalpine fir trees based on the X-ray CT imaging. However, CTSTEM presents a new, flexible method for integrating automatic image analysis (feature extraction) with 3D modelling and visualization of subalpine fir stems and serves as a useful promotional tool to highlight the advantages of internal log scanning for detection and visualization of hidden morphological features of large logs.

With respect to sustainable forest management applications, conventional forestry is based on handful of commercially valuable species that in many areas have logged out. To sustain forests over the long term, multi-species, instead of selected ones, need to be harvested without depleting any particular species. Therefore, in the near future, Canada’s forest industry will increasingly be forced to utilize species of trees that were once underutilized or considered “less reputable” species such as subalpine fir in B.C. Effective utilization of the non-traditional subalpine fir species is essential for successful sustainable forest management.
The main reason for the limitation of effective utilization of subalpine fir has been a great difficulty in obtaining and manipulating accurate information on 3-D internal positions of wetwood while the log geometry, density, numbers and positions of other key stem components such as knots and branches change as a result of tree growth. The developed first component of CTSTEM using CT data, overcomes these constraints by providing means to nondestructively quantify the internal qualities of tree stems and logs for measuring variation in log/stem properties for scaling and grading of logs, and the strategic allocation of a given wood resource to a suitable forest industry. CTSTEM also provides means for improved industrial utilization of its wood as a raw-material (sawlogs, pulpwood and bio-energy production) through determination of variation in material properties of trees and logs which can also be linked to silvicultural management, tree growth, and harvesting. It provides a new insight for detection and measurement of 3-D positions and parameters of morphogenesis, which generate wetwood patterns in a context of the other stem components. These parameters obtained from CTSTEM can be used to create ‘virtual subalpine fir stems” models containing knots, wetwood, branch patterns and can be linked to structural and functional tree models for simulations of the structural dynamics of individual tree component in 3-D space. Therefore, CTSTEM provides 3D quantitative parameters for understanding of wet-wood formation in a context of components of tree structure (stem, knots, and branches) which would provide knowledge for designing forest management that aims at improving subalpine fir forest health, growth yield and increase the production of high quality timber, which is essential for successful sustainable forest management.

In addition to providing mathematical bases to obtain useful information about internal structure of logs/stems based on the CT data, the second component of the CTSTEM provides mathematical simulation base lines for studying and evaluating commercially available on-line X-ray Log Scanners (two- and three fixed source), and still under development (cone-beam scanner) X-ray Log Scanner for industrial applications. The simulated X-ray Log Scanners based on two and three-fixed X-ray sources are very promising in a sense that these X-ray scanners may fulfill the demand on speed and makes it possible to sort subalpine fir logs according to quality properties. In Europe, there are sawmills, which have already installed industrial X-ray scanners based on two fixed X-ray sources and two and three-fixed source linear array detectors applying fan-beam geometry.

Overall, the developed subalpine tree model, CTSTEM, composed of two main components provide means to achieve the original aims of this study for improved industrial utilization of subalpine fir stems by advancing scientific knowledge in its wood properties through the innovative technologies and approaches: first, to determine 3D variation of wetwood and knots within subalpine fir stems using industrial CT images of logs. Second, to evaluate feasibility of simulated X-ray scanner for sorting subalpine fir logs. Therefore, CTSTEM provide new insight for integration between the forest sector and the forest industry through the development of strategic modelling and simulation of material property variation in standing trees grown under differing growth conditions and processing of logs in-line applications. These will not only enhance the traditional technologies offered the industry equipment that forestry and wood operations process raw material with higher volume using traditional resource standard; but also for the long run, it provides a new modeling and simulation of technological means that can be used to evaluate the forest value and increase the value of wood products produced using equal or less resource and therefore CTSTEM enhances the bottom-line results of sustainable forest management.
7 References


APPENDIX

Tree Data and Site

Wentworth Creek Site Description

- 50° 59´ N  120° 23´ W
- ~70 km north of Kamloops, within Weyerhaeuser’s TFL 35
- elevation: 1210 – 1220 metres
- Thompson Plateau physiographic area
- Central Dry climate region
- BEC classification: MSdm2 = Montane Spruce, dry mild subzone, Thompson Plateau variant
- slope: 25%
- mesoslope position: lower slope
- aspect: NNW (330°)
- timber type (from Weyerhaeuser forest cover map): Pl(B) 6316–20
- average breast-height age (Pl): 105 years
- estimated site index: 25.3 at BH age 50
- estimated total age: 110 years

Wentworth Creek Subalpine Fir tree Measurements

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Note: crown class I = Intermediate  C = Codominant

volumes were computed using BCMOF taper equations for subalpine fir
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