Coarse-Resolution CT Scanning for Sawmill Logs Sorting and Grading

by

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Abstract

Significant economic advantage can be achieved by grading logs at the inlet of a sawmill so that they can be optimally processed to manufacture the highest possible value products from the available raw material. At present, log inspection is mainly based on visual observation of surface defects and optical measurement of external features. Such inspection is time-consuming and many quality-controlling features are not visible on the surface, thus very much prone to error.

Computed Tomography (CT) has been extensively used as a medical diagnostic tool, and increasingly used for scientific and industrial research. In the wood industry, there is a growing interest in using the CT technique to assess the quality of logs entering a sawmill. Internal features of interest include knots, heartwood/sapwood boundary, rot and splits. Most commercially available CT scanning systems are modeled on medical designs and provide high spatial and density resolution. However, they are very complex and delicate and their cost is correspondingly high. The extreme scanning speed requirement, moderate affordability and severe working environment in a sawmill make medical style CT scanner unsuited for sorting and grading applications.

Log scanning is not as challenging as medical scanning because most targeted internal features are fairly large and have specific geometrical shapes. A suitable log scanner for this task must be simple, rugged and economical. Based on these thoughts, a novel coarse-resolution CT scanning approach is developed in this thesis. The research work includes designing and constructing a practical CT log scanner, developing coarse-resolution log models, customizing log CT data processing techniques and designing and implementing efficient reconstruction algorithms.
The prototyped log scanner and the coarse-resolution density reconstruction results will be demonstrated in this thesis. Such reconstructions reveal internal features inside the log and provide rich information such as knot size/location, sapwood/heartwood extent, localized and averaged internal densities. The results also compare well with CT reconstructions using the same measurement with conventional filter-back-projection algorithm. The good comparison gives confidence in the usefulness and applicability of the proposed approach for practical sawmill logs sorting and grading application in the future.
Preface

The papers submitted for publications from this thesis originated from the author’s Ph.D. research conducted under the supervision of Dr. Gary Schajer. The relative contributions of the author and supervisor in this research project and publications are clarified in this section.

Three papers have been submitted for publication on academic journals: Paper I: [An, Y.] and Schajer, G.S. Geometry-Based CT Scanner for Measuring Logs in Sawmills. This paper is based on the content elaborated in Chapter 2 and Chapter 6; Paper II: [An, Y.] and Schajer, G.S. Coarse-Resolution Cone-Beam CT Scanning of Logs Using Lagrangian CT Reconstruction: Part I: Discretization and Algorithm. This paper is based on the theoretical work introduced in Chapter 2, 4 and 5; Paper III: [An, Y.] and Schajer, G.S. Coarse-Resolution Cone-Beam CT Scanning of Logs Using Lagrangian CT Reconstruction: Part II: Hardware and Demonstration. This paper is based on the research work introduced in Chapter 3 and Chapter 6. The author drafted all three papers and Dr. Schajer revised and finalized them. All three papers are currently under journal peer-review process.

Dr. Schajer originally proposed the coarse-resolution log scanning concept. Originating from this concept, the author achieved the detailed scanning design and implementation work in his research. In his research, the author developed coarse-resolution log models, novel log scanning geometry (chapter 2), designed and constructed a prototype log CT scanner (chapter 3), developed and formulated novel CT data processing technique (chapter 4) and reconstruction algorithm (chapter 5) and implemented the log scanning test and demonstrated results (chapter 6). Dr. Schajer supervised the research and offered great help and guidance in solving the practical challenges during the evolution of the project. Dr. Schajer also contributed significantly in revising and improving the writing of this thesis.
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List of Symbols

I  Attenuated X-ray intensity
I₀  Unattenuated X-ray intensity
β  Basis weight coefficient (kg/m²)
ρ(x)  Density at position x (kg/m³)
G  Path-length matrix
G_{ij}  (i,j) components in matrix G
(x_d, y_d)  Pixel coordinates in barrel-distortion image
(x_u, y_u)  Pixel coordinates in barrel-distortion corrected image
K₁, K₂, K₃, K₄  Barrel-distortion correction coefficients
Xᵢ  Pixel coordinate on X-ray detector plane
D_{SD}  Distance between X-ray source and detector (m)
W_D  Large format detector width (m)
ψ  X-ray cone illumination angle (radian)
d_{BW}  Basis weight data
d_C  CT data (logarithm of the ratio between attenuated and unattenuated data)
r_{rad}  Log angular radius (radian)
dψ  Angular spacing between detector pixels (radian)
R_{Log}  Estimated log radius (m)
D_{SL}  Distance between X-ray source to log center (m)
c  Estimated circumferential centroid position in the basis weight graph
δ  Basis weight center-shifting amount (radian)
c_{raw}  Centroid position in raw basis weight graph
\(c_a\) Centroid position in adjusted data

\(r_{pix}\) Log radius in angular pixels

\(d_{BW}^{\text{std}}\) Basis-weight data under “standard log” view

\(d_{BW}^{\text{norm}}\) Basis-weight data after normalization

\(m\) Total number of annuli in annular reconstruction model

\(n\) Total number of sectors in sector reconstruction model

\(s\) Total number of slices within the cone beam

\(p\) Total number of data measurement within each projection;

\(r_k\) The sequence of annulus radii

\((X_i, Y_i, Z_i)\) Pixel coordinates at cylindrical detection surface

\(\alpha\) X-ray inclination angle with respect to Z-plane (radian)

\(S_{In}\) Inclined voxel path-length (m)

\(S_{Proj}\) Projected path-length (m)

\(G_{SBa}\) Single-slice basic path-length sub-matrix for annular model

\(G_{SBs}\) Single-slice basic path-length sub-matrix for sector model

\(G_{SBr}\) Single-slice basic path-length sub-matrix for combined model

\(G_{MBa}\) Multi-slice basic path-length sub-matrix for annular model

\(G_{MBs}\) Multi-slice Basic path-length sub-matrix for sector model

\(G_{MBc}\) Multi-slice Basic path-length sub-matrix for combined model

\(G_n\) Path-length sub-matrix on the nth projection direction

\(G_{Sa}\) Single-slice annular geometry full path-length matrix

\(G_{Ss}\) Single-slice sector geometry full path-length matrix

\(G_{Sc}\) Single-slice combined geometry full path-length matrix
$G_{Ma}$  Multi-slice annular geometry full path-length matrix
$G_{Ms}$  Multi-slice sector geometry full path-length matrix
$G_{Mc}$  Multi-slice combined geometry full path-length matrix
$d_{BW}^s$  Single-slice basis weight data vector
$d_{BW}^M$  Multi-slice basis weight data vector
$A$  Resultant path-length matrix
$A_{Sa}$  Single-slice annular geometry resultant path-length matrix
$A_{Ss}$  Single-slice sector geometry resultant path-length matrix
$A_{Sc}$  Single-slice combined geometry resultant path-length matrix
$A_{Ma}$  Multi-slice annular geometry resultant path-length matrix
$A_{Ms}$  Multi-slice sector geometry resultant path-length matrix
$A_{Mc}$  Multi-slice combined geometry resultant path-length matrix
$b$  Converted basis weight vector
$b_{Sa}$  Single-slice annular geometry converted basis-weight vector
$b_{Ss}$  Single-slice sector geometry converted basis-weight vector
$b_{Sc}$  Single-slice combined geometry converted basis-weight vector
$b_{Ma}$  Multi-slice annular geometry converted basis-weight vector
$b_{Ms}$  Multi-slice sector geometry converted basis-weight vector
$b_{Mc}$  Multi-slice combined geometry converted basis-weight vector
$L$  Lower triangular matrix with real and positive diagonal entries.
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<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>BW</td>
<td>Basis weight</td>
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<tr>
<td>I.I.</td>
<td>Image intensifier</td>
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<tr>
<td>FPXD</td>
<td>Flat panel X-ray detector</td>
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<tr>
<td>CCD</td>
<td>Charge-coupled device</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary metal-oxide semiconductor</td>
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<tr>
<td>IC</td>
<td>Integrated circuit</td>
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<tr>
<td>EMCCD</td>
<td>Electron multiplying charge-coupled device</td>
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<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
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<tr>
<td>CHHM</td>
<td>Center for hip health and mobility</td>
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<tr>
<td>VGH</td>
<td>Vancouver general hospital</td>
</tr>
<tr>
<td>NCRP</td>
<td>National council on radiation protection and measurement</td>
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<td>DAQ</td>
<td>Data acquisition</td>
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Dedicated to:

My Wife Jun Xie;

My Parents Kang An and Ying Sun;
Chapter 1: Introduction

1.1 Overview of Log Sorting and Grading

The successful running of a sawmill is critically dependent on its ability to achieve the highest possible value recovery from the sawmill logs. The sawmill industry in US and Canada is a multi-billion business [1]. However, the pressures from steadily rising timber costs, declining wood supply and increasing customer demand for products with special properties have greatly increased the challenges on the sawmill industry [2]. Sawmill industries across the world have struggled to find ways to reduce raw material wasting and to increase the yield value from raw logs [3].

Wood is a highly variable natural material that requires an individual decision for each wood piece to identify the most advantageous processing method. In this way the most appropriate and highest value products can be produced from the available raw material. Log inspection is mostly based on visual observation of surface defects [4, 5]. In Europe, sawlogs can be classified into 30 grades based on visual observation [6]. Then the logs are cut into different sawn products according to their observed characteristics [7, 8]. However, many quality-controlling features are not visible on the surface, causing the sorting and grading to be far from optimal. A skilled log inspector may judge a lot about the internal quality of a log by viewing its appearance, but the frequency of misjudgments is high. Studies indicate that only half of inspected logs are classified correctly by human inspectors [9]. Consequently, many logs are placed at the wrong breakdown position, dramatically reducing the amount of high-value products obtained. It is estimated that the value of sawn timber could increase by 7-15% if the internal defects in logs were accurately known [10, 11]. This is a massive value increase and urgently points to the need for an effective log scanning tool.
Sawmill operators in different countries have very clearly expressed their need for effective and efficient log sorting and grading tools that are capable of detecting internal features in real time and of providing information to design the optimum sawing pattern of each input log [8].

1.2 Current Log Scanning Technology

Non-destructive tests have become popular in wood scanning and testing fields in recent decades. Methodologies including optical scanning, ultrasound, X-rays and CT scanning have been applied to log scanning. Significant work has been done to validate their effectiveness for industrial application.

1.2.1 3-D Optical Log Scanning

Among different scanning modalities, three-dimensional optical scanning has become a mature technique and been used in many sawmills. An optical scanner measures the surface shape of the log and provides detailed information about log geometry and evenness of the log mantle area [12]. From optical scanning, log type, butt-end taper, “bumpiness” and “knottiness” can be inferred [13]. However log sorting and grading is an internal-feature driven process. External features can help to infer internal features, but do not provide direct measurements, thus they lack accuracy for indicating internal structures. It has been reported that the percentage of correct sorting from optical scanner ranges between 50% and 60% [13, 14], slightly higher than visual inspection, but still not an effective tool for internal log scanning applications.

1.2.2 Ultrasonic Log Scanning

Ultrasound scanning is a popular medical diagnosis tool and has also gained successful application in industrial testing for forest products operations. The ultrasonic practice detects the acoustic responses of the measured object to externally applied excitation. Research on using
ultrasound scanning for log scanning has been implemented by different research groups [15, 16]. By measuring ultrasonic velocity and energy dissipation, internal structures inside the log and their corresponding properties can be determined. However, ultrasound waves travel very poorly through air, so the technique requires applying liquid gel to transmit the sound waves from the transmitter to the surface of the log [16]. The difficulty of coupling an ultrasound transmitter to the logs greatly limits its usage in real sawmill environments.

1.2.3 X-ray Log Scanning

X-ray is an effective tool to reveal internal structures within scanned objects. By measuring the X-ray attenuation through the object of interest, a 2-dimensional plan view can be obtained. X-ray scanning has the vast applications in both the medical field (chest X-ray, mammography, C-arm fluoroscopy, etc.) and the industrial field (airport security checking, luggage/shipment inspection and pipeline examination, etc.) [17].

![X-ray Log Scanner and Sample X-ray Image: (a) Log image, (b) 3-direction X-ray log scanner](image.png)
X-ray scanning was introduced for log scanning in the sawmill industry in 1990s [18]. Since then it has become the primary tool for internal log scanning and has had several successful applications in sawmills. The first generation design of X-ray log scanner uses a single X-ray source and an X-ray line-scan camera. The log translates through the source-detector assembly during the scanning. This arrangement is very similar to airport luggage inspection systems and is still the most common log scanning technology on the market. However X-ray scanning is highly directional and it only provides measurement along the X-ray penetration direction. All the features inside the log will be projected into this direction and get overlapped on each other. Figure 1.1 (a) shows one example of an X-ray log image. This image gives useful interpretation of internal features inside the logs. Clusters of knots show up clearly as dark areas in the image. However, one cannot identify the knots’ exact location in the out-of-plane direction due to the overlapping nature, thus missing the information needed to choose the most advantageous sawing pattern required for subsequent log processing.

Grundberg and Grönlund (1995) proposed an X-ray log scanning system using two sets of X-ray source and line-scan camera assemblies, placed 120° apart around the log [19]. This initiated the trend of X-ray log scanning to the stage of using multiple source-detector assemblies. Figure 1.1 (b) illustrates a typical 3 source-detector assembly log scanner setup. Holtec [20] from Germany and Bintec Oy [21] from Finland developed their log scanning system by using 4 and 6 source-detector assemblies placed around the log. Their scanner is reported to be capable of running at throughput speeds of 1-3 m/s and measuring under-bark diameter, knot cluster volume and average ring width.

X-ray systems using multiple source-detector assemblies allow extension beyond single direction measurements. However, this arrangement greatly increases the capital cost of the
technology. A four-source-detector log scanning system from Bintec Oy is currently priced at $800,000 and that is an excessive cost for most sawmills. Apart for the issue on affordability, four or six fixed projection measurements still provide limited amounts of data. Limited data make the feature extraction within the log require careful modeling and approximation. Correct interpretation of these images needs a lot of extra information and careful examination. The ambiguity due to lack of data limits such systems’ scanning sorting accuracy.

Except industrial development, much research work has also been done in the X-ray log-scanning field. Most of the research studies are implemented to fetch useful internal information from limited X-ray projection measurements. Pietikäinen (1996) proposed a vector-based knot geometry model and developed a detection method by using simulated three X-ray measurements projected 120° apart from each other [22]. However, this approach tends to give artifacts due to the limited number of measurement directions. In addition, the model is designed only for knot detection and cannot identify rot or moisture content variation. Researchers from Eigenor cooperation proposed a statistical inversion method to extract internal features inside the log [23]. They claimed by using 4 or 6 different X-ray directional measurements, a useful cross-section view of the log can be extracted. But based on their presented results, the scanned image is very noisy and lacks stability to apply to practical log scanning.

1.3 Computed Tomography (CT) Log Scanning

Computed Tomography (CT) is a powerful technique to create 2-dimensional cross-sectional views of an object from multiple 1-dimensional X-ray measurements called “projections” (usually 500-1000 projections are used per cross-section reconstruction). These 2-D views reveal the internal features within the object. By translating the object along the axis of
rotation and making projection measurement at each interested position, a 3D volume of the object can be formed by mathematically combining all reconstructed slices [24].

There is a growing interest in using the CT technique to assess log quality in sawmills [25]. The features of interest include knots, moisture content and sapwood/heartwood extent, splits, etc. These features have a different density than that of the surrounding clear wood and the difference can be observed clearly in the CT reconstructed cross-section images. Figure 1.2 gives an example to demonstrate the effectiveness of CT log scanning. Figure 1.2(a) shows a cross-section view of clear wood region. A high-density sapwood region and a relatively low-density heartwood region can be clearly observed. Figure 1.2(b) shows a cross-section of log with 4 small knots appearing on the top half. In both images, the reconstructed cross-section view is very detailed and in addition to the dominant features described above, smaller features such as growth rings and local variations can also be clearly observed.

![Figure 1.2 CT Slices of Log: (a) Clear wood region, (b) Knot region (image courtesy of G. Szathmary, FPInnovations)](image)
Due to the rich information provided by CT scanning, it is likely that industrial CT scanning will be the next generation of log scanning tool for the sawmill industry [26]. Research in the CT log scanning area has been a thriving field and work has been done on both of the measurement side [27, 28] and on the data analysis side [29, 30]. Automated feature extraction algorithms, defect recognition methods [31] and CT-slices based sawing pattern optimization [32] software have been designed and implemented.

Despite the strong research interest of applying CT technology to sawmill industry, most work in this field focuses on off-line experiments with medical CT scanners to gain justification for more practical research. Most research focuses on using the CT reconstruction data in a post-analysis to segment features of interest. As yet, no simple in-line CT systems for log inspection have been developed.

### 1.3.1 Medical Style CT Scanner

Most CT scanners are designed for medical use or research purpose, for which feature identification in the sub-millimeter range is essential. This requirement makes most of medical or industrial scanner much more complex, costly and computation-intensive than is practical for log sorting and grading applications. Medical style CT scanners are delicate and requires lots of maintenance, thus not suitable for the severe working environment in a sawmill.

Despite the financial and complexity issues mentioned above, the biggest challenge hindering the direct application of CT scanning to log inspection is the imaging speed. Successful CT reconstruction requires substantial projection data, but in a sawmill scanning must be done with logs that move at production speeds (1-3m/s), thus there is very limited time available to obtain a sufficient number of projections to reconstruct a cross-section accurately.
In medical scanning, scanning resolution is the most important issue and scanning speed can be compromised to gain higher reconstruction resolution. But for log scanning, the requirement is opposite. Figures 1.3 (a), (b) and (c) respectively show a medical-style 3rd generation single-slice fan-beam CT scanner [33], a typical cone-beam CT scanner [34] and a 7th generation spiral multi-slice scanner [35]. For all three scanning geometries, the object of the measurement, commonly a patient in a hospital but here a log, translate along the central axial direction and an X-ray source and a line or a multi-slice area detector rotates simultaneously around the outside to gather the multi-directional series of radiographs for the CT reconstruction. These designs all require that the X-ray source and detector accurately rotate around the measured object so as to maintain accurate spatial registration among the radiographs measured from the various directions. As a result, the X-ray source and detector rotation speed becomes the most limiting factor to increase scanning speed. Although spiral multi-slice CT scanner increases the scanning speed by using multiple detector arrays (increased detection area, up to
256 detector arrays), it is still only capable of scanning at a few cm/s at a decent resolution. This is not an applicable speed in sawmill due to the substantial volume of incoming logs and extremely high throughput speed (1-3m/s) [36]. Except for the speed, high cost of CT scanner is also a huge barrier for CT as a sawmill optimization application.

1.3.2 Existing Computed Tomography (CT) Based Log Scanning Approaches

It has been a long struggle to find a practical way to apply CT scanning to log inspection. Both industrial and academic researchers have made their approaches. The first approach followed the medical CT scanner design principle. Microtec [37] simulated a CT log scanner using a spiral multi-slice setup very similar to Figure 1.3(c). Based on their simulation, this CT scanner should be able to scan up to 2m/s using a (1.35m x 0.75m) X-ray area detector with a rotation speed at 6 rev/s. However, fabricating such a scanner is very difficult. Both customizing an X-ray detector to that scale and rotating the source-detector assembly and acquiring quality data at that speed are very challenging.

The second approach is to design an unconventional CT geometry system and novel reconstruction method. Seger (2003) introduced the design of a log scanner composed of two perpendicularly arranged X-ray source - 2D detector systems [38]. Each of the 2D detector systems comprised 33 line-scan x-ray detectors placed 5mm apart, thus creating a large area, low resolution and fast readout area detector. Seger also rearranged the attenuation data and applied a coarse version of Fourier slice reconstruction. Results using synthetic data showed a good capability of identifying the locations and shape of knots inside the log. However the model proposed there is very theoretical. A total of 66 line-scan X-ray scanners are quite costly, not really an economical setup. Also due to the perfection of synthetic data, it is hard to evaluate the performance of the reconstruction technique when real measurements are applied. But this
approach points to new direction on the path of seeking practical CT log scanning method: novel CT scanning geometry and customized CT log reconstruction algorithm.

1.4 Log Scanning Challenges and Opportunities

Most CT scanning systems on market are modeled on medical designs. They are very delicate, complex and expensive. The associated CT reconstruction is computationally intensive requiring massive data collection, processing and data analysis. They provide high spatial and density resolution but are slow on scanning speed, requiring high-precision motions of sensors and specimen and demanding on maintenance and a good working environment.

Different from medical scanning, a successful log sorting and grading application in sawmills sets its own requirements on the scanning system. First, it requires stable detection of internal features. Second, it should be able to accommodate a wide range of sizes of logs. Third, the scanning system should work in real time without slowing down the sawing process. This means that the analysis time for each log must not exceed the scanning time. The total time span for scanning and CT reconstruction is only 5-10 seconds per 5m log. Fourth, such system should be rugged and robust. It should tolerate significant rigid body motions during log transmission and require less maintenance than what a medical style CT scanner would require. Last but not least, the CT log scanner should use straightforward design and equipment making it affordable to most of sawmills.

Industrial CT log scanning is a very challenging task but the special object “logs” also offer some great features to apply such technology. The level of detail required by log sorting and grading is very different than medical CT scanning. In logs, the main features to be identified are knots, sapwood/heartwood boundary and rots, all of which have dimensions measured in centimeters, thus only a very coarse resolution scanning process is needed. Very
importantly, logs have very specific geometry; they are circular in shape and all features of interests have their own specific shapes, thereby making available much a-priori information. The coarse spatial resolution requirement and geometry specific information greatly reduces the amount of scanning data needed and offers great opportunities to design log geometry based CT reconstruction algorithms. These key features open up the opportunity of economical real-time coarse-resolution CT scanning in sawmills.

1.5 Purpose and Scope of the Research

The conventional CT log scanning approach is to use a medical or industrial CT scanner to scan the log and to compute the CT cross-sectional image, and then to analyze the CT image to identify the internal feature information. Thus, this approach makes the scanning and feature extraction as separated phases. However, what the sawmill industry needs is an integrated system that is practical, economical and will be able to scan and realize feature detection together in real time.

The purpose of the research presented in this thesis is to design and prototype a novel coarse-resolution CT system that is capable of detecting log internal features and can potentially meet sawmill industry’s log scanning requirement. Unlike the conventional approach of adapting current CT technology, a different approach is taken here: customize a CT scanner specifically for logs. This work includes both designing and constructing a customized CT log scanner and developing CT log model and corresponding algorithm. The objective is to provide an all-in-one coarse-resolution CT log scanning system that will enable the further development of practical in-line CT log scanning in the future. In this context, “coarse resolution” means a spatial resolution of around 5mm, which should be sufficient to identify the existence and location of features such as knots that have diameters in the 1-4cm range. In contrast, medical scanners have
spatial resolutions in the 0.5mm range, which is onerously fine for log scanning. Detailed research work will be introduced in the following chapters.

Chapter 2 describes the coarse-resolution CT scanning concept, the novel geometry-based CT log models, the general density inversion computation and the evolution of this research path. Chapter 3 introduces the hardware design of the proposed log CT scanner. The prototype CT log scanner is demonstrated. Chapter 4 presents the customized CT data processing method. The main focus is on applying an “standard log view” processing and a “Lagrangian” data alignment and normalization technique. Chapter 5 presents the path-length based density reconstruction algorithm. It gives the derivation of path-length matrix formulation and direct matrix multiplication. Chapter 6 demonstrates CT reconstruction results from sample log scanning tests. The effectiveness of the proposed CT log scanning system is validated in this chapter. Chapter 7 states the main conclusions and contributions. The extent of the present research is concluded and the future extensions and needs are discussed.
Chapter 2: Coarse-Resolution CT Log Scanning Concept

2.1 Overview

Computed Tomography (CT) theory, techniques and applications have undergone a rapid development over the past two decades [39]. A successful CT scanning application includes three essential parts: reliable X-ray projection measurements, reconstruction model and geometry, and supporting reconstruction algorithms. Most CT scanners are medical designs or modeled on medical designs. With medical CT scanners, the human scanning object limits the choice of scanning motion and data collection. The X-ray source and detectors have to rotate simultaneously around the patient while the patient is translated through while lying on a bed. The choice of reconstruction geometry for medical CT scanning is aimed at revealing very small abnormalities of general geometry. A fine square-grid pattern is a mathematically convenient choice. For the reconstruction algorithm, the filtered back projection procedure has become the standard method for CT computation because of its easy implementation [40] and smaller computational burden compared to the iterative Algebraic Reconstruction Technique (ART) [41].

In Chapter 1, it was indicated that log CT scanning allows more design freedom than medical CT scanning. As a particular object, logs have some advantages. Logs are inanimate, so they can be moved and maneuvered conveniently. They also have specific geometry, which is known in advance ("a-priori"). Logs are cylindrical and most of the features of interest are relatively large, in the centimeter range, and have specific geometric shapes. These features provide a good opportunity to customize efficient log CT scanning. This chapter presents the proposed geometry-based coarse-resolution CT log-scanning concept. “Coarse-resolution” refers to two aspects of this approach: first, the X-ray projection measurements requested for a successful CT computation are coarser than what are needed for conventional CT measurements;
second, the required spatial resolution is coarser. The geometric CT log models correspond directly with the physical log internal features so the number of voxels needed to represent a log cross-section is much coarser than what is needed in conventional CT geometry. Detailed work is presented in the following sections.

2.2 Coarse-Resolution Log Scanning Concept

Figure 2.1 Proposed Log CT Scanning System

Figure 2.1 shows the schematic of the proposed log CT scanning system. The design strategy is to use straightforward equipment so as to make the required scanner hardware more practical and robust. This proposed log scanning system uses a cone-beam, collimated X-ray source, a lab-made large-area X-ray detector and a log transport and spiral motion mechanism. The log to be inspected is translated and rotated simultaneously within the cone-shape illumination space between the X-ray source and detector. During the spiral motion of the log, X-ray images are taken at a series of incremental angles, from which the log cross-sections along the full length are reconstructed. The arrangement in Figure 2.1 has three complementary features that makes it dramatically different from medical CT scanner design:
1. log spiral-motion mechanism. Unlike a medical scanner, a stationary source and detector is used. Instead of rotating X-ray source and detector and translating the object, the log is maneuvered into spiral-motion and gets viewed from different angles. This avoids the difficulty of generating high speed, complex and meticulously controlled rotation of X-ray source and detector, which is the main limiting factor for medical CT scanning speed.

2. large-angle cone-beam X-ray illumination. The greater cone-beam illumination allows using a larger fraction of the available X-rays, thus reducing the X-ray wastage and the X-ray power needed for a given overall illumination. This reduces radiation safety concerns and gains better efficiency for X-ray power usage.

3. large-format area detector. The use of a large-format detector dramatically increases the scanned volume and so makes possible the simultaneous reconstruction of many slices and a much higher scanning speed. Mechanical details of the proposed log CT scanner hardware design and construction will be described in Chapter 3.

2.3 Geometry-Based Coarse-Resolution Models

The a-priori information provided by knowledge of the specific geometry of logs allows substantial computation economy through the use of geometry-based CT models. The conventional CT approach has a fixed reconstruction geometry. The typical geometry is the square-grid pattern shown in Figure 2.2(a). The X-ray attenuation coefficient at each square, called a “voxel”, is determined (“reconstructed”) from the X-ray measurements and this coefficient can be converted into voxel densities if needed [42]. This generalized geometry is chosen because it accommodates internal structures of any geometry and maximizes the resolution to identify fine features of interest. A further characteristic of this geometry is that it is fixed in space. By analogy to finite element modeling, this may be described as “Eulerian”
because the mesh pattern is referenced to a fixed volume in space and the log passes through this space. Under this arrangement, features inside this space are required to stay still during the projection measurements. Extraneous motions during the measurements will cause blur and artifacts in the reconstruction [43]. This explains the reason why it is usual to give CT scan patients the instruction “hold your breath and keep still”. Thus, conventional CT geometry forces the scanning to be done in a very carefully controlled environment. However, such precise control of motions is not practicable in a sawmill. The irregular saw-logs move quickly on the transmission belt and the substantial lateral rigid-body motions are inevitable.

The a-priori information available with saw-logs makes possible the use of some simpler feature-specific log cross-section models instead of the commonly used fine-meshed square pattern. In areas away from the knots, logs are generally circular with axi-symmetric cross-sectional features. Where present, the knots start from the center and grow approximately in a sector shape through the perimeter. Based on these observations, three coarse-resolution, geometry-based CT log models are proposed here. These three geometric models target different internal features. The first model shown in Figure 2.2(b) comprises annular regions. This arrangement is suited for the clear wood regions between knots, where heartwood/sapwood, rings and rot tend to be axi-symmetric. The second model shown in Figure 2.2(c) comprises sector-shaped regions. This arrangement is suited to the knot regions where the features are sector-shaped. Figure 2.2(d) shows a combined model, which is suitable when multiple features are present simultaneously. All three log models divide the cross-section into feature-specific regions and tend to guide the resulting cross-sectional reconstructions towards physically realistic solutions. The smaller number of unknown voxels compared with the generic square
grid shown in Figure 2.3(a) dramatically reduces the quantity of X-ray measurements and the size of the computation.

![Figure 2.2 Log Geometric CT Models: (a) Annular model, (b) Sector model, (c) Combined model, (d) Conventional model](image)

**2.4 General Density CT Computation**

The proposed geometry-based log models are non-conventional and there are no existing algorithms fitting well with them. Consequently, customized algorithms need to be designed to implement the proposed approach. Figure 2.3 depicts the X-ray path in each of the log models.
Figure 2.3 X-ray Path in Log CT Models: (a) Path length in annular geometry, (b) Path length in sector geometry, (c) Path length in combined geometry

X-rays fan out from the source, pass through the log and reach the large-area detector. The part of the log within a given X-ray path attenuates the radiation according to the line integral of the density along that path [44]. The relationship between X-ray attenuation and log densities can be expressed using Beer’s Law as Equation (2-1), where \( I \) is the attenuated X-ray intensity, \( I_0 \) is the unattenuated intensity, \( \rho(x) \) is the log density along the path length at position \( x \), and \( \beta \) is the basis weight coefficient (kg/m\(^2\)) [45].

\[
\frac{I}{I_0} = \exp\left(-\int \frac{\rho(x)dx}{\beta}\right)
\]  

(2-1)

The coefficient \( \beta \) corresponds to the basis weight at which the attenuation equals 37%. This occurs when the exponent in Equation (2-1) equals -1. Equation (2-1) can be linearized by taking logarithms on both sides:

\[
\int \rho(x)dx = -\beta \ln\left(\frac{I}{I_0}\right)
\]  

(2-2)
where the left side of Equation (2-2) represents the line integral of the material density along the X-ray path. This quantity corresponds to the local basis weight (= density per unit area). The right hand side represents the basis weight data, which is the product of the basis weight coefficient $\beta$ and the logarithm of the X-ray attenuation ratio. It is useful to distinguish the X-ray measurements and basis weight data. X-ray measurements indicate the attenuation, the more the attenuation, the less intense the X-rays reaching the scintillator. Basis weight data reflect the line integral of density along the X-ray paths, the bigger the integral, the more the attenuation, and the higher the value. This is the reason why X-ray radiographs and CT slices are black-and-white inverted.

Equation (2-2) can be discretized and written for the given ray as:

$$\sum g_j \rho_j = d_i$$  \hspace{1cm} (2-3)

where $g_j$ is a set of discrete lengths corresponding to material densities $\rho_j$ within a sequence of voxels along the overall ray path. The quantity $d_i$ is the basis weight observed for the given ray according to the measured X-ray attenuation. Figure 2.3 (a-b-c) shows the X-ray path and line section in annular, sector and combined voxel in a path of ray $i$ measurement. For the voxels X-ray passed, the discrete length can be computed from geometry. For the non-visited voxels, the discrete length set to be zero. For the combination of all the rays within the X-ray cone, Equation (2-3) can be generalized as:

$$\sum G_{ij} \rho_j = d_i$$  \hspace{1cm} (2-4)

where $G_{ij}$ is a matrix whose entries represent the path length within ray “$i$” as it passes through voxel “$j$”. This equation can be expressed in vector-matrix format as:

$$[G]\{\rho\} = \{d\}$$  \hspace{1cm} (2-5)
where brackets and braces respectively indicate matrix and vector quantities.

Equation (2-5) represents the essence of CT reconstruction: using the measured basis weight data to reconstruct unknown CT number or densities. Normally, the path length matrix \([G]\) is a very large matrix, with number of rows equals to the number total X-ray measurements and the number of columns equals to the number of voxels. Modern CT uses large detector arrays (256, 512, 1024 detectors per array, etc.) and received projections from substantial number of directions (500, 1000, etc.) \([46]\). At the same time, the number of voxels is also maximized (512x512, 1024x1024), consequently, \([G]\) is a matrix with elements in the million range. In such circumstances, direct inversion of equation (2-5) would be a very demanding computation process. Thus, in conventional CT practice, Equation (2-5) is not solved directly. Instead, a filtered back-projection based analytical approach is normally taken to compute the unknown voxels indirectly. Here, in the present work, the number of X-ray measurements and voxels is much smaller because of the coarse-resolution arrangement and feature-specific shapes, so a direct solution becomes a practical choice. Chapter 5 of this thesis provides technical details on formulating the path length matrices and direct computation of voxel densities using proposed log CT models and reconstruction geometry.

2.5 “Standard” Log View Concept

A very important approach throughout this thesis that substantially reduces the computational burden of the CT reconstruction is the novel “standard log view” concept. Logs are made of a natural material and so are not perfect, with significant non-circularity. In conventional CT approaches, these geometrical variations are computed and so are automatically contained within the CT reconstruction.
The proposed log “standard” view ignores small physical variations and utilizes the same standardized cross-sectional view (Figure 2.3) to process the basis weight data and form the path-length information from all measurement projections. This influences the CT reconstruction in two aspects:

1. The “standard” log view makes it possible to normalize (standardize) the CT measurements to fit the log models. Under this arrangement, the voxels in Figure 2.2 (b-c-d) are not referenced to the fixed space but referenced to the “standard log”. By analogy to finite element modeling, the proposed approach may be described as “Lagrangian”. This approach enables some pragmatic approximations to be made when processing the measured data to compensate for the lateral rigid-body motions that occur when rough saw-logs are moved within sawmills. Chapter 4 presents the CT data normalization methods and motion compensation algorithms in details. It will be shown how this procedure substantially compensates for lateral rigid-body motions and log non-circularity.

2. The “standard” log view makes it feasible to reuse the computed path-length within each log cross-section view. Due to axi-symmetry of the proposed coarse resolution models, if arranged with some consideration, the interaction pattern between the X-ray and log model at different projection angle remains consistent, thus the path-lengths computation need only be performed once. This dramatically reduces computation scale of [G] matrix in Equation (2-5). Chapter 3 will introduce the sector-boundary triggering procedure, which allows the repetition of the same X-ray path-length pattern. Chapter 5 will explain the details to compute the path-length matrix from the “standard” log view.
2.6 Evolution of Coarse-Resolution CT Log Scanning Research

Figure 2.4 Evolvement of the Research on CT Log Scanning and Reconstruction: (a) Single-slice CT reconstruction, (b) Multi-slice cone-beam CT reconstruction, (c) Multi-slice spiral-motion cone-beam CT reconstruction

The ultimate goal of the present research is to have a coarse-resolution cone-beam spiral-motion log scanning system that is capable of effectively identifying log internal features in real-time. To achieve this goal, three stages of work are planned:

1. build a prototype log CT scanner according to the design shown in Figure 2.1,
2. realize effective X-ray measurements and data processing to fit with coarse-resolution log model,
3. develop and implement effective log CT reconstruction.

Parts 1 and 2 have been completed. Part 3 is partially completed and remains in progress. Figure 2.4 shows the evolution of log CT reconstruction (Part 3) in this research. The three intermediate stages are single-slice reconstruction, multi-slice cone-beam reconstruction and multi-slice spiral-motion cone-beam reconstruction. This evolution also complies with the conventional CT technology development path in the past 40 years. So far, single-slice reconstruction, multi-slice cone-beam reconstruction parts have been developed and validated. They are explained and demonstrated within the scope of this thesis. The multi-slice spiral-
motion cone-beam reconstruction is a direct extension from multi-slice cone-beam reconstruction. It is planned as a future work.

2.7 Conclusion

This chapter introduces the key features of the proposed coarse-resolution log CT scanning design. The work includes hardware prototyping, model design and algorithm development. The proposed approach and method is novel in the sense of tailoring CT technology to saw-log scanning. It addresses the design of a log-motion oriented scanning system and effectively using “a-priori” information from log geometry to simplify the reconstruction algorithm and increase the computation speed. The effectiveness of this approach will be validated from sample log scanning results. Details of this research work will be presented in the following chapters.
Chapter 3: CT Log Scanner Hardware Design, Control and Demonstration

3.1 Overview

Chapter 2 proposed the main concept of coarse-resolution spiral-motion CT log scanning. This novel design uses a stationary X-ray source - detector assembly and generates a spiral-motion trajectory of the scanned log to avoid the complex mechanical design required to rotate the X-ray source and detector. To fully implement the schematic design, evaluate the approaches proposed and procure a practical system that could be modeled and applied in sawmill industry, a CT log scanning system has been prototyped under laboratory conditions. This system closely follows the conceptual design shown in Figure 2.1.

This chapter will elaborate and explain the research work done on CT system design and implementation, which includes:

- design/customize a large-format detector,
- design/fabricate a log rotation/spiral-motion mechanism,
- design/implement scanner control and data acquisition scheme, and
- accomplish radiation safety shielding.

3.2 Large Area Detector

The core part of the proposed CT scanner is the large-format high-speed detector. To achieve this requirement, various X-ray imaging techniques and the state-of-art technologies were examined in detail.

3.2.1 Commercial X-ray Area Detectors

X-ray detection technologies have been highly evolved and updated in the past three decades. Photographic plates have been substantially replaced by digital X-ray detectors [47, 48]. Among different X-ray detection modules, X-ray image intensifiers and flat-panel X-ray
detectors have become the most popular and prevailing detector types. The X-ray Image
Intensifier (I.I.) consists of input window, input phosphor, photocathode, vacuum and focusing
electrodes, output phosphor and output window [49]. An I.I. is capable of amplifying an X-ray
scintillated low-light scene into a visible image. Flat-panel X-ray detectors (FPXD) have
emerged as the latest generation of digital X-ray technology. They comprise X-ray scintillators,
photo-diodes and thin film transistors. The design is based on solid-state integrated circuits (IC),
similar in many ways to the imaging chips used in visible wavelength digital photography and
video [50]. Both I.I. and F PXD provide an indirect detection method. The scintillator converted
the X-ray into low-level visible light and the light was either amplified and recorded by CCD or
CMOS camera or detected by very sensitive photodiodes. Both I.I. and FPXD generally are
designed for medical purposes (mainly for chest X-ray), therefore they have very fine spatial
resolution and a limited imaging frame rate. At present (2013), I.I. is priced above $30,000 [51]
and FPXD is priced above $100,000 [52], costs that make such detectors economically
challenging in the sawmill industry.

Despite the financial burden, the practical obstacle of using commercial digital X-ray
detector for log scanning is the limitation on the detection area. In sawmills, the low end of the
diameter range for saw-logs is 15-45cm [53], so allowing for the enlargement caused by the cone
shape of the X-ray illumination and adding some free space at the edges, a minimum detector
size needed is 60cm across. At present, I.I and FPXD are manufactured in limited sizes: the
largest I.I goes up to 16’’ (about 40cm) diameter and the largest FPXD reaches 43cm x 43cm
detection area. Thus to form a log scanning detector, several commercial I.I or FPXD must be
used at the same time. This dramatically multiplies the cost of possessing such technology in
sawmills, not mentioning the difficulty of registering and synchronizing different detector pieces
at real time. Thus the use of such detectors is not a practical approach. It is likely that the cost of such detectors will eventually reduce as electronic technology advances, but likely the size limitation will remain because the medical application dominates the market.

There are some other approaches on the path of seeking an appropriate X-ray detector for log scanning. Seger [38] proposed using many line detectors placed together to form an area detector, but this approach gives quite sparse data in the longitudinal direction and uses a low fraction of the incident X-ray beam, although greater than with a single line detector. The cost of acquiring many X-ray line detectors is also unattractive. Tate (2005) proposed making an area X-ray detector by coupling an X-ray scintillator and CCD chip using a fiber-glass taper, and demonstrated the idea by making a sample 2” x 2” area detector [54]. But scaling up this approach to a 60cm x 60cm detector is not practical because of the enormous size of the required fiber-glass taper.

3.2.2 Scintillator-EMCCD Camera Design

An alternative approach has been taken here to produce a large-format X-ray detection design [55]. Under this design, a detector has been customized, which provides the desired combination of moderate spatial resolution, high-speed, high sensitivity at moderate manufacturing cost.

The proposed system consists of a large area scintillator phosphor screen, a reflection mirror and an EMCCD (Electron Multiplying Charge-Coupled Device) camera. Figure 3.1(a) shows the schematic design. In this design, the scintillator attenuates the X-rays that pass through the log and proportionally converts them into visible light. The mirror reflects the light and allows placement of the camera outside the primary X-ray radiation path. The EMCCD camera detects the low-level light from the scintillator and forms a 2-D measurement set.
The major challenge of this design comes from the X-ray detection efficiency [56,57]. In typical flat-panel X-ray detectors, the solid-state detection circuitry (photodiodes+thin film transistor) is placed immediately under the scintillator, thereby capturing a large fraction of the available light. However, in the proposed design, only a very small fraction of light emitted from the X-ray scintillator reaches the lens and is captured by the camera. Therefore, finding and matching high-response scintillation material with a sensitive camera becomes an important task.

Different scintillation materials were tested and compared. Figure 3.2(a) shows a comparison of three different common scintillation materials used to image a metal washer fixed within an open space. The left half of the figure shows the scintillation image measured using Gd$_2$O$_2$S:Tb 250 micron thick, the top right quadrant shows the image using CsI 500 microns thick, and the bottom right quadrant shows the image using NaI 1mm thick, all when energized by the same amount of X-ray radiation (40kVp, 5mA). It is found out that 500 micron CsI is the brightest, however it has substantial blur due to the light scattering inside the material. NaI has a spectrum in the blue light range, not matching well with the peak sensitivity of most image...
sensors. The material is also hygroscopic and therefore needs to be protected from moisture absorption. Gd$_2$O$_2$S showed good brightness, contrast and less blur, it is also easy to fabricate into a large screen, and thus stands out as the choice for our scintillator screen. A 60cm x 60cm (Gd2O2S: Tb) screen from Kasei Optonix, Ltd, Japan [58] is used in actual customized detector.

![Image](image_url)

**Figure 3.2 Scintillation Materials and EMCCD:** (a) Composite X-ray image of a metal washer to compare the characteristics of different scintillation materials, left half = Gd$_2$O$_2$S 250 micron thick, top right quadrant = CsI 500 microns thick, bottom right quadrant = NaI 1mm thick, (b) Andor iXon EMCCD camera

A pilot test showed that a conventional CCD camera is not sensitive enough to detect the dim light from the scintillator. Electron Multiplying Charge-Coupled Device (EMCCD) offered a greatly improved light detection capability. EMCCD works like a conventional CCD except that it provides an internal gain via an electron avalanche mechanism [59]. As such, an imaging system based on the EMCCD does not require the use of the intensification stages, even though it still provides detection of extremely low light levels. An important advantage of EMCCD is that it effectively reduces the measurement noise by the gain factor (around 1000 linear gain adjustment), therefore improving the output signal-to-noise ratio (SNR). Also the deep cooling of the detector (-80°C) minimizes the dark current, with a total noise less that 1e$^{-}$. EMCCD employs a pixel binning function as a conventional CCD does, thereby further increasing effective light...
sensitivity and enabling image acquisition at higher frame rates. Among different EMCCD camera products, Andor iXon 897 camera [60] was selected and installed into the customized X-ray detector.

Figure 3.3 Scintillator-EMCCD Detector: (a) Customized detector, (b) Sample log image

Figure 3.3 (a) shows the custom-made scintillator-EMCCD detector. An enclosure (1mx1.2mx1.2m) was made to house all the required components and to seal them from interference by ambient light. The interior was painted matte black to reduce stray light reflections, while the outside was painted white for convenience. The Gd2O2S (white shiny panel in Figure 3.3(a)) is fixed in the upright position and a reflection mirror is placed diagonally behind. The EMCCD camera is mounted inside a lead-shielded box and installed into the X-ray detector enclosure. All the components were adjusted and aligned with the X-ray source position. Figure 3.3 (b) shows a log X-ray sample image acquired from the customized detector. The good contrast and clear field of view proves the effectiveness of the proposed detector design. In this image, the dark areas indicate high material density (high X-ray absorption) and conversely the bright areas indicate low material density (low X-ray absorption). The vertical dark regions near
the center indicate the knots within the log section and the horizontal bright gap shows a large radial crack.

This scintillator-EMCCD detector design is economical and robust, and it works very well, as is shown in more detail in Chapter 6. A very important feature of this design is its detection area scalability. The particular X-ray detection area depends on the size of the scintillator screen. This size can be scaled up or down as needed, with some corresponding adjustment to the camera optics to image the detection area. Thus, the detector can easily be adapted to measure either very large or very small logs.

### 3.3 Log Motion Mechanism: Linear Motion, Rotation and Spiral Motion

Another important element of the log scanning approach proposed in Figure 2.1 is realizing rotation and spiral-motion generation directly with the log. As described in Chapter 2, this conveyor must be able to realize log linear-motion (radiograph style scanning), pure-rotation (single-slice, multi-slice pure rotation scanning) and spiral-motion (multi-slice spiral-motion scanning).

Figure 3.4(a) shows the customized log conveyor. This conveyor consists of a log mounting cart driven by a double stepper-belt system. The log sample with end plates is mounted on the rotation shaft of the carrier cart. A guidance track is fixed on the lab floor. Two PowerPac 1.8º NEMA 34 steppers are installed on both end of the track. One transmission belt is coupled with two motors and clamped with the cart, thus moving the conveyor back and forth for linear motion; a second transmission belt is fixed at both ends and wrapped around the pulley mounted with the log, thus mechanically coupling the rotation motion to the linear motion, shown in Figure 3.4(b). As the stepper motor starts to turn, the first belt pulls the cart for linear motion and the second belt forces the log to rotate with a spiral pitch equal to 35cm. This system offers the
varieties on log motion control and generation. For linear motion, only the first belt is used; for pure rotation, a separate stepper can be installed at one side of the cart, forming another stepper-pulley-belt mechanism to drive the rotation of the log, shown in Figure 3.4(c); for spiral motion, two belts are engaged and set to work together.

Figure 3.4 Log Spiral-Motion Conveyor: (a) Spiral-motion carrier, (b) Stepper motor and belting mechanism, (c) Pure-rotation position
3.4 Log CT Scanner Control Scheme

![Log CT Scanner Control Hardware: (a) Encoder, (b) Central control console](image)

Figure 3.5 Log Scanner Control Hardware: (a) Encoder, (b) Central control console

The large-format detector and the log motion mechanism are the essential stand-alone parts of the scanner hardware. A system integration and control scheme was designed and implemented to run this system and achieve the proposed scanning task. Figure 3.5 shows the encoder and central control console. The rotary encoder (US Digital S1 optical encoder) is coupled with the rotation shaft to track the log angular position. The control console box houses the power supply units, encoder reader board, microcontroller unit, supporting control electronics (digital I/O, signal conditioning, etc.)

3.4.1 Sector Boundary Triggering

The use of a shaft encoder enables the design of a rotation-angle-based data registration scheme: sector boundary triggering. This is an essential part of the implementation of the “standard” log view concept proposed in chapter 2. The approach is to use the rotary encoder to trigger X-ray measurements (frame acquisition from the EMCCD camera) at the angular intervals chosen to match the sector CT model proposed in Figure 2.2. In this way, for all three proposed reconstruction models, the scanning geometry at each measurement remains the same,
other than an integer rotation of the sectors. Figure 3.6 illustrates the feature of geometry preservation under this scheme. It can be observed that the path lengths of the X-rays are exactly the same within the sector model, apart from a rotation of the sector numbering. Chapter 5 will give a mathematical description on how to use the fixed path-length pattern to formulate and store the large path length matrix efficiently for subsequent reconstruction computation. An important further advantage of this angle-based procedure is that it makes the data acquisition insensitive to log rotation speed, thereby enabling accurate data registration even during non-uniform speed log motion.

![Figure 3.6 Encoder Based Sector Boundary Triggering](image)

### 3.4.2 Scanner Control Design

A control scheme was designed and implemented to synchronize the various hardware components and to realize successful control over the customized log CT scanner. Figure 3.7 demonstrates the flow chart of this control scheme. Control graphical user interface software was written by the author and installed on a desktop computer. During log scanning, the shaft encoder monitors the log rotation and triggers the EMCCD camera to acquire an image after each sector rotation. These images are then transmitted and saved in the desktop computer for subsequent data processing and CT reconstruction.
To prevent stepper motor slippage [61] when starting or stopping the heavy log, an incremental speed-control scheme was implemented to provide a controlled log rotation speed with appropriate acceleration and deceleration [62]. Using this scheme, the log conveyor prototype was capable of driving a sample log weighing 100kg at up to a 2Hz rotation speed and 70cm/s translation speed.

3.5 Scanner Shielding Design

Radiation safety shielding is an essential feature of a practical CT scanner. Safe operation of the log CT scanner requires a good and validated shielding design. The Centre for Hip Health and Mobility (CHHM) at Vancouver General Hospital (VGH) kindly granted this project lab space to set up the customized log scanner equipment. The allocated room was not initially designed for radiation tests, thus there was no existing shielding. Consequently, it was necessary to design a customized shielding system for the prototype log scanner. Figure 3.8 shows the schematic design. The shielding consists of 11 movable lead panels surrounding the log scanner. The lead panel thicknesses and location at primary radiation and scattering direction panel location are determined based on the design procedures recommended by National Council on
Radiation Protection and Measurement (NCRP) [63, 64]. All panels are made of plywood panel with lead sheets installed on both sides and casters mounted underneath (shown in Figure 3.9 (b)). The whole system passed the radiation safety inspection from *Radiology Matrix Consulting Ltd* [65], a designated agency from VGH. A radiation validation report was issued.

![Figure 3.8 CT Log Scanner Shielding Design](image)

### 3.6 CT Log Scanner Setup

![Figure 3.9 CT Log Scanner Prototype: (a) Schematic design (recap), (b) System overview](image)

By putting together the large-format detector, the log motion conveyor, the scanner control electronics and the safety shielding, the proposed novel log CT scanner is in place to use.
Figure 3.9 (a) recaps the proposed log scanning system and Figure 3.9 (b) shows the corresponding experimental setup of the prototype scanner. For the actual log scanner prototype, the X-ray source and detector are placed left and right instead of up and down as shown in the schematic drawing. The cone-beam X-ray source used is a Comet MXR industrial X-ray system with 160kVp, 10mA maximum capacity. The white detector box is aligned with the X-ray source on the right. A sample log is secured on the log motion conveyor in the middle. Lead-lined X-ray shielding panels surround all equipment to provide radiation safety. The supporting control and data acquisition electronics, and a CT inversion computer system are placed behind the shielding panels. When scanning starts, the X-ray source is switched on continuously and the conveyor drives the log into the needed motion (rotation, spiral motion, etc.). The encoder is read in real time to track the log position and at every sector rotation, image data are captured from the detector side.

3.7 Conclusion

This chapter has introduced the hardware design, control and implementation of the prototype CT log scanning system. The smooth operation and satisfactory data acquisition validates the effectiveness of this log scanner prototype. As a summary, Table 3-1 shows the detailed list and descriptions of all hardware components used in the author’s design.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Component Name</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray Source</td>
<td>X-ray tube</td>
<td>Comet MXR X-ray source</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target angle: 20°, Focal spot: 0.4mm, 1.5mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tube voltage: 160kVp, current: 4mA – 10mA</td>
</tr>
<tr>
<td></td>
<td>Generator</td>
<td>Philips MG-160 Generator: 160kVp (max.), 10mA (max.)</td>
</tr>
<tr>
<td>Detector</td>
<td>Scintillator</td>
<td>Kasei Optonix Gd$_2$O$_2$S screen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dimension: 60x60cm, Phosphor Deposit Thickness: 350 micro</td>
</tr>
<tr>
<td>EMCCD</td>
<td>Andor iXon 897,</td>
<td>Resolution: 512x512, Frame rate: 30fps</td>
</tr>
<tr>
<td>Detector Box</td>
<td>Movable enclosure box</td>
<td>Dimension: 1m x 1m x 1.2m</td>
</tr>
<tr>
<td>Log conveyors</td>
<td>Shaft(2)</td>
<td>1.25” diameter, 1’ length</td>
</tr>
</tbody>
</table>
## Table 3.1 CT Log Scanner Hardware Components

Although the log CT scanner is a first-generation prototype, there are some favorable features making it promising and practical for future industrial application. First, it uses simple design and straightforward equipment. Fabricating and assembling such system is much less complex compared with the effort required for conventional medical or industrial CT scanners. Second, the design is economical, notably through its use of a stationary X-ray source and large-format detector. Third, it offers the flexibility over the area of X-ray detection, this makes it cover a wider range of sizes of logs. And last, this design separates the X-ray detection and log motion (rotation, spiral-motion) into stand-alone modules, thus removing the obstacle of limiting scanning speed due to rotating the heavy X-ray source and detector assembly while making measurement simultaneously. The scanning data from the proposed log scanner together with the

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Component Name</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>Stepper Motor(2)</td>
<td>PowerPac 1.8º NEMA 34 stepper motor, Nominal rating: 24volts, 10Amps</td>
</tr>
<tr>
<td></td>
<td>Motor Driver(2)</td>
<td>US Digital MD2S Micro-stepping Driver</td>
</tr>
<tr>
<td></td>
<td>Bearing(2)</td>
<td>1.25” shaft diameter, 1.875” center height</td>
</tr>
<tr>
<td></td>
<td>Pulley</td>
<td>18-tooth pulley @ 3/8” pitch, 36-tooth pulley @ 3/8” pitch</td>
</tr>
<tr>
<td></td>
<td>Timing Belt</td>
<td>Macmaster Carr L-series 1 inch belt</td>
</tr>
<tr>
<td></td>
<td>Cart</td>
<td>IKEA Bekvam kitchen cart (2)</td>
</tr>
<tr>
<td>Electronics</td>
<td>Encoder</td>
<td>US Digital S1 Shaft encoder: 720 counts per revolution</td>
</tr>
<tr>
<td></td>
<td>Encoder DAQ/ IO</td>
<td>US Digital USB4 board: 4 incremental encoders (5 MHz input frequency), 16 digi/O, 4 ADC channels, 4 DAC channels</td>
</tr>
<tr>
<td></td>
<td>Power Supply</td>
<td>LGB G Scale Regulated Power Supply: 24 Volts, 6.5 Amps</td>
</tr>
<tr>
<td></td>
<td>Micro-controller</td>
<td>ATmega 103L 8 bits microcontroller: 16 bit timer; 8bits I/O ports</td>
</tr>
<tr>
<td></td>
<td>Laser Switch</td>
<td>Automation Direct FFRP-BN-1E photoelectric sensor: 4 meter detection range, NPN transistor</td>
</tr>
<tr>
<td></td>
<td>Computer Station</td>
<td>DIY Desktop PC: Intel Core 2 CPU @ 2.89GHz, 8.0 GB installed memory, Windows 7 operation system</td>
</tr>
</tbody>
</table>
reconstruction results using a novel coarse-resolution approach (Chapters 4 and 5) will be demonstrated and presented in Chapter 6.
Chapter 4: Log CT Scanning Data Processing

4.1 Overview

Chapter 3 introduced the X-ray log scanner hardware design and control. The measured quantities are the X-ray attenuations caused by the interaction with the material within the X-ray propagation direction. These measurements must be processed and converted to basis weight data before applying CT inversion.

The novel coarse-resolution approach taken in this project requires customized data processing and also brings up new opportunities of creatively utilizing the data to facilitate the subsequent CT reconstruction. If done with some care, the proposed data processing can also mostly eliminate the effects of log ellipticity and lateral rigid-body motions of the log within the X-ray beam, which can be very damaging in conventional CT measurements. These are very favorable features and will be introduced in detail in the chapter.

4.2 Barrel Distortion Correction

To increase the field of view, a very short focal length lens (8mm) is installed in front of the EMCCD camera in the customized detector. This dramatically shortens the distance between scintillator and camera, making it a lot more compact. However, this also introduces “barrel distortion” due to optical aberration within the wide-angle lens [66]. Figure 4.1(a) shows a raw image from the camera when viewing a square-grid sheet. The barrel effect is most apparent at the edges of the image.
A common way of describing barrel distortion mathematically is in the form of a polynomial series [67].

\[ x_u - x_c = (x_d - x_c)(K_1r^3 + K_2r^2 + K_3r + K_4) \]  \hspace{1cm} (4-1)

\[ y_u - y_c = (y_d - y_c)(K_1r^3 + K_2r^2 + K_3r + K_4) \]  \hspace{1cm} (4-2)

\[ r = \frac{\sqrt{(y_d - y_c)^2 + (x_d - x_c)^2}}{d_{img}} \]  \hspace{1cm} (4-3)

where, \((x_d, y_d)\) are the coordinates (pixel indices) of a pixel point in the distorted image (input image), \((x_u, y_u)\) is the corresponding pixel point in the undistorted image (destination image), \((x_c, y_c)\) represents the centre and \(r\) is the distance between the point of interest and the image center, normalized by image dimension \(d_{img}\).

The dimensionless polynomial coefficients \((K_1, K_2, K_3, K_4)\) can be determined by solving the linear equations if the coordinates of distorted and undistorted points are determined. A calibration test was done to determine the polynomial coefficients. In this test, a known grid with fixed spacing and pattern was imaged by the EMCCD camera. The true location of points of interest was determined based on the spacing of the grid pattern and the coordinates of the
distorted points were picked out in the captured image. Then, a least-squares analysis was conducted to find the best-fit coefficients. The coefficients were then used to correct later captured images from the EMCCD camera under the same physical setting. Figure 4.1(a) shows the barrel distorted grid pattern used for the calibration test and Figure 4.1(b) shows the undistorted grid image achieved after applying the correction. The correction described by Equations (4-1) to (4-3) is seen to be very effective for removing the barrel effect and restoring the true image geometry.

### 4.3 Cylindrical Adjustment

![Figure 4.2 Flat and Cylindrical X-ray Detectors: (a) Side view, (b) Axial view.](image)

For convenience of manufacture and to provide a consistent object plane for the camera, the large-area detector has a flat detection surface (60cm x 60cm scintillator screen). In this arrangement the image pixels have equal spacing on the detection plane. For the CT inversion, a more convenient arrangement is for the pixels to have equal angular spacing in the cross-sectional plane of the log. To realize this, the flat detection surface must be mathematically converted into a cylindrical surface whose axis passes through the X-ray source parallel to the
longitudinal direction of the log. This adjustment gives the detector panel a circular symmetry to complement the circular symmetry of the log model.

Figure 4.2(a) illustrates the proposed cylindrical adjustment in side view and Figure 4.2(b) shows the corresponding mathematical quantities in axial view of log scanning. Measurements $X_i$, which are linearly spaced on a flat panel detector, can be mathematically adjusted so that they appear to be equally spaced at angles $\theta_i$ on an equivalent cylindrical detector. This is a fixed geometrical relationship:

$$X_i = \frac{D_{SD}}{W_D/n} \tan(\theta_i - \frac{\psi}{2}) + \frac{n}{2}$$  \hspace{1cm} (4-4)

where $D_{SD}$ is the distance between source and detector, $W_D$ is the detector width, $n$ is the number of detectors within the detector width, and $\psi$ is the X-ray cone illumination angle subtended by the detector width. The corresponding X-ray data $I[i]$ at angular pixel “i” is evaluated from the integral of the linear X-ray data $I_{x-ray}(x)$ bounded by the given angular pixel

$$I[i] = \frac{\int_{x_{i-1}}^{x_i} I_{x-ray}(x)dx}{x_i - x_{i-1}}$$  \hspace{1cm} (4-5)

This arrangement is applied column-by-column to all pixels to create the arrangement shown in Figure 4.2 (b). The nature of coarse-resolution reconstruction greatly reduces the amount of data needed. The EMCCD had a 512x512 resolution CCD chip. In practice, a 128x128 resolution image provides enough data for the proposed CT reconstruction, so the linear spaced 512 pixels in each column are interpolated into a 128 equal angular spaced pixels to form the mathematically curved detection surface. A 1x4 hardware binning can also be taken in the longitudinal direction to further increase the detection area per pixel (better signal to noise ratio),
and increase the frame rate. The result is a 128 pixel dimension in both longitudinal and transverse directions.

4.4 X-ray Measurement and Basis Weight Data

Direct log X-ray measurements can be obtained when scanning logs using the proposed CT scanner. These measurements are X-ray attenuation values and they must be converted into basis weight (mass per unit area) values before being used for the CT reconstruction. Equation (2-2) in Chapter 2 shows the relationship between the line integral of density and basis weight, where the basis weight is:

\[ d_{BW} = -\beta \ln\left(\frac{I}{I_0}\right) = -\beta \times d_C \]  

(4-6)

\[ d_C = -\ln\left(\frac{I}{I_0}\right) \]  

(4-7)

In Equation (4-6), the basis weight data \( d_{BW} \) is composed of two parts: the basis weight coefficient \( \beta \) (“mass attenuation coefficient” in classic CT books) and the logarithm of the ratio of the attenuated and unattenuated X-ray intensity data, \( d_C \). For the convenience of explanation, \( d_C \) is called CT data here.

Formulating CT data is a straightforward process. It involves taking the negative logarithm of ratio of attenuated and unattenuated X-ray intensity data. Figure 4.3 (a) shows the X-ray measurement with the log existing in the field (attenuated data) and Figure 4.3(b) shows the X-ray measurement where the log is absent in the field (unattenuated data). Barrel distortion correction and cylindrical adjustment are previously applied to both data. By taking negative logarithm pixel by pixel, a CT data image \( d_c \) can be formulated.
Figure 4.3 X-ray Raw Data and CT Data: (a) Raw X-ray log measurement, (b) Unattenuated X-ray reference, (c) Converted CT log data

One practical problem in formulating CT data is X-ray intensity drift. This was a particular issue in the present measurements because the X-ray source used was an older model and did not have a tight control of the emitted X-ray intensity. Variations in X-ray power caused the X-ray intensity to fluctuate up to 10%. This fluctuation caused difficulties because the attenuated and unattenuated X-ray measurements were taken at different times, and so did not give closely comparable measurements. A data-scaling scheme was created to remove the effect of this power level drift. The small rectangular boxes shown in Figure 4.3(a) and (b) represent regions outside the log where it is expected that the same X-ray intensity should exist in all images. Then the attenuated and unattenuated X-ray data can be scaled to the same level based on the average of the pixels within the four rectangular boxes. Figure 4.3(c) shows the CT data formulated from the X-ray measurements in Figures 4.4(a) and (b). This image has been color inverted, with greater brightness indicating greater basis weight. The black regions at the top and bottom indicate areas outside the log, corresponding to zero basis weight.

CT data needs to be further converted into basis weight to apply to reconstruction computation. This requires knowing the coefficient $\beta$ explicitly. $\beta$ is determined by the material
atomic number and the X-ray energy level [68]. However, wood is composite material, composed of about 50% carbon, 6% hydrogen, 44% oxygen and trace amounts of metal ions [69] and the emitted energy spectrum from the X-ray source was polychromatic, so the coefficient $\beta$ cannot be determined easily.

Figure 4.4 Basis Weight Calibration Test: (a) Calibration Test, (b) Scanned image, (c) Basis weight vs. CT data curve

An alternative approach is to form a CT data to basis weight data relationship by a calibration test. Figure 4.4(a) demonstrates the test and Figure 4.4(b) shows the X-ray measurement of the wood samples. The samples used are medium density fiberboard (MDF) with known density and dimensions. These boards are stacked within the beam to form a known series of basis weights. The corresponding CT data can be obtained by scanning these boards at the energy level for the log-scanning test and performing the logarithm computation. Then the basis weight vs. CT data curve can be computed. Figure 4.4 (c) graphs the calibration curve. For monochromatic X-rays this curve would be linear, but for polychromatic X-rays, the curve bends outward with an increasing gradient due to beam hardening [70]. This curve links the X-
ray measurement directly to basis weight data. At each pixel, once the CT data are computed, the corresponding basis weight data can be determined uniquely.

4.5 Basis Weight Data Normalization

One particular challenge in CT application is how to deal with data affected by rigid-body motions [71]. Rigid body motions are very damaging and cause blur in the reconstructed images [72]. For most medical CT scanners, very accurate control is exercised over the motion of the scanner and specimen to minimize this effect. However, in sawmills, the fast throughput speed, severe working environment and handling of the rough logs make it impossible to control the log motions with high precision, thus rigid body motions are inevitable.

In Chapter 2, a “standard” log view concept was briefly introduced. The main part of this concept is the normalization of the basis weight data. This proposed normalization method will be elaborated here. The method estimates the log radius and center from basis weight data and compensates the adverse effects of rigid-body motion by re-centering and normalizing these data into a standard format.

4.5.1 Rigid-Body-Motion Removal and Ellipticity Compensation

The use of the geometrical CT models in Figure 2.2(b-c-d) and the circular symmetry of the cylindrical panel detector in Figure 4.2 (a-b) enable mathematical accommodation of the effects of rigid-body motions by adjusting the arrangement of the basis weight data. Figure 4.5 illustrates the proposed method in the log cross-section view. For example, consider a small circumferential motion of a log relative to the center of the X-ray fan shown in Figure 4.5(a). The effect is to shift the measured basis weight data along the arc of the X-ray detector from A-B to A’-B’. The radiograph image seen between A’-B’ is the same as would have been seen
between A-B had the rigid-body motion not occurred. Thus, a circumferential rigid-body motion can simply be corrected by shifting the radiograph image between pixels A’-B’ back to the pixels A-B, which for convenience is assumed to be in the center of the cylindrical panel detector.

Similarly, for radial rigid-body motions such as in Figure 4.5(b), the effect of the motion is to expand the basis-weight image A-B to A’-B’ (or contract it for an outward radial motion). Thus, a radial rigid-body motion can be corrected by scaling the basis-weight image circumferentially between pixels A’-B’ to the pixels A-B. This scaling concept can be taken a step further to accommodate logs that are slightly elliptical. The arc length A’-B’ of the basis-weight measurements in Figure 4.5(c) caused by a non-constant log diameter can similarly be scaled to fit the arc length A-B. The adjustment is not perfect because of small angle changes within the X-ray fan, but for modest rigid-body motions and log diameter variations, the process is quite effective.

Figure 4.5 Measurement Re-centering and Uniform Scaling: (a) Circumferential motion, (b) Radial motion, (c) Ellipticity effect
4.5.2 Log Radius and Center Position Estimation

The ability to do the rigid-body motion and log ellipticity compensation shown in Figure 4.5 depends on an ability to identify the log position and diameter within the basis weight graph.

Figure 4.6 Basis Weight Profile and Elliptical Approximation

Figure 4.6 shows a typical basis weight data profile within one log cross-section and it has an approximate semi-ellipse shape. The horizontal axis represents the equal angular spaced pixel index and the vertical axis represents the basis weight data. The simple way to obtain center and radius information is through image edge detection. However, this is unreliable because the image edge information depends on just a small number of local pixels. These may be subject to noise, especially if some local irregularity exists at that point on the log, such as due to a branch or loose bark. A more robust approach is to estimate the log angular radius (in radians) from the entire basis weight data profile. This can be done by assuming that the log is circular and of uniform density (physically not exactly true, but appears to be good
computational approximation). Then the log basis weight data forms a semi-elliptical shape profile shown by the blue line in Figure 4.6. Its area $A$ is proportional to radius $\times$ axial height, while its centroidal height is proportional to axial height only. Dividing the area $A$ by the centroidal height $y$ gives a robust estimate of the log angular radius $r_{rad}$:

$$r_{rad} = r_{pix} \cdot d\psi = \frac{8A}{3\pi^2 y} d\psi = \frac{16}{3\pi^2} \left( \sum d_{BW}^2 \right)^2 d\psi$$

(4-8)

$$R_{Log} = D_{SL} \sin (r_{rad})$$

(4-9)

where $r_{rad}$ is the angle span of the log radius in the basis weight profile, $r_{pix}$ is the number of angular pixels that the log radius occupies, $d\psi$ is the angular spacing between detectors after cylindrical adjustment, $R_{Log}$ is the estimated log radius, $D_{SL}$ is the distance between X-ray source to log rotation center and again $d_{BW}$ are the basis weight data.

The estimated circumferential position of the centroid in the basis weight graph gives the log centre position:

$$c = \sum \frac{id'_{BW}}{\sum d'_{BW}}$$

(4-10)

where $i$ is the angular pixel index.

4.5.3 Data Re-centering and Normalization

Based on the reliable log center and radius estimation, the normalization method can be implemented. Figure 4.7 (a) illustrates the data shifting and Figure 4.7(b) shows the normalization approach. The idea is to shift the basis weight data so that the log appears as if it were in the center of the field, and to scale the data so that the log appears as if it had a “standard” diameter.
Figure 4.7 Basis Weight Normalization: (a) Data re-centering, (b) Re-scaling and normalization

Equation (4-11) computes the basis weight center-shifting amount $\delta$, where $c_{raw}$ and $c_a$ are the centroid position in raw and adjusted data. Equation (4-12) computes the normalized pixel position and Equation (4-13) calculates the normalized basis weight data, where $n$ is the total number of normalized pixels and $i$ is the index.

$$\delta = c_a - c_{raw} \tag{4-11}$$

$$x_i = \frac{r_{pix}}{n} \times i \tag{4-12}$$

$$d_{BW}^{std} = \frac{\int_{x_{i-1}}^{x_i} d_{BW}(x)dx}{x_i - x_{i-1}} \tag{4-13}$$

Because basis weight data represents the line integral of the densities, log radius estimation directly affects its quantity. To compute the same material densities for the “standard” log and the actual log, the basis weight data needs to be reciprocally scaled with respect to the ratio between actual and “standard” diameter so that the same amount of mass is represented within the resulting basis weight data. Equation (4-14) shows this calibration
The proposed normalization scheme gains computational efficiency by wrapping the data in a compact and “standard” form. These estimated log radii and the center-shift amounts at each log cross-section are recorded and this information can be used to unwrap the “standard” log reconstruction back to the “actual” log reconstruction. Besides forming data in a standard form, this also opens the opportunity to pursue to concept of arranging Equation (2-5) in a standardized form, where the path length matrix $[G]$ is the same for all sizes and positions of logs. Further discussion and implementation of “standard” log view concept on path-length matrix will be continued in Chapter 5.

4.6 Conclusion

The general concept and procedures of CT data processing for log scanning is introduced in this chapter. The approach taken here is highly customized and is substantially different from conventional methods. Barrel-distortion correction is first performed to the X-ray measurement; cylindrical adjustment is then implemented to simulate a curved detection surface with equal angular space pixels. Afterwards, X-ray data are converted into the basis weight measurements based on the basis weight vs. X-ray attenuation curve obtained from a calibration test. In the end, data are re-centered and normalized in a “standard” diameter log format and arranged into the basis weight vector $\{d\}$ in Equation (2-5).

The data processing approach taken here is an approximate one. Examination of the path lengths shown in Figure 2.3 shows that the diameter of the log relative to the X-ray source to detector distance and the position of log center do have some influences on relative path lengths, beyond just a simple multiplier based on log diameter. However, for the small ray angles that

$$d_{BW}^{\text{norm}} = d_{BW}^{\text{std}} \times \frac{R_{\text{std}}}{R_{\text{Log}}} \quad (4-14)$$
occur when the X-ray source to detector distance is much greater than the log diameter, this effect is modest. The data normalization method taken is a “Lagrangian” approach, whereby the CT reconstruction is based on the moving log. The approach makes it very tolerant of rigid body motion and log ellipticity. This is very unusual in the CT inversion because the data are centered and referenced to the “standard” log and not to a fixed volume in space, as is done in conventional practice. Good reconstruction results using CT data processed by the proposed method validate the effectiveness of such data processing and will be presented in Chapter 6.
Chapter 5: Path-Length Matrix Formation and Density CT Reconstruction

5.1 Overview

Chapter 2 briefly overviews the proposed log CT density reconstruction. Equation (2-5) shows the governing equation for all CT inversion problems. Conventionally CT reconstruction is done indirectly by either analytical reconstruction such as filtered-back-projection (FBP) or iterative solution such as algebraic-reconstruction-technique (ART) [73]. The use of geometry-based coarse-resolution models greatly reduces the computation scale and thus makes a convenient direct computation method feasible.

This chapter will elaborate the details of the geometry-based coarse-resolution CT reconstruction approach. It will start from single-slice reconstruction case and then generalize it to multi-slice cone-beam reconstruction. It will first introduce the path-length computation within “standard” log view, and then use it to formulate all sub-matrices that comprise the full path-length matrix \([G]\). A least-squares method is taken to compute the densities. Instead of explicitly formulating the very large matrix \([G]\), the product matrix \([G]^T[G]\) is formulated directly using the basic path-length sub-matrix from the “standard” log view. In the end, a Cholesky solver is applied to solve the linear system. Technical details and procedures will be explained in the following sections.

5.2 Voxel Path-Length Computation

Chapter 4 explained the CT data processing technique, which provides the basis weight data vector \([d]\) on the right side of Equation (2-5). The next step towards completing the CT reconstruction is to assemble the path length matrix \([G]\). A successful CT reconstruction requires to image the object from many different directions and a single directional X-ray measurement is
called a “projection”. Thus, to build the G matrix, voxel path lengths need to be determined within each projection based on the scanner and coarse-resolution model geometry.

5.2.1 Path-Length within “Standard” Log View

In previous chapters, the “Standard” log view scanning concept has been introduced. Driven by this thought, both data acquisition (sector boundary triggering) and data processing (basis weight normalization) have been designed. A very important feature of “standard” log view is that it greatly simplifies the computation involved in formulating the path-length matrix. It saves the tedious path-length calculation at different projections. Instead, the computation only needs to be done once within the “standard” view.

5.2.2 Single-Slice Path-Length Computation

\[
 r_k = \sqrt{\frac{(k+1)}{m}} R_{\text{Log}} \quad 0 \leq k \leq m - 1
\]
where \( m \) is the total number of annuli. In this way, the areas of the annuli are equal, thereby approximately weighting the path length at each annulus for a balanced computational accuracy of the material densities. The path lengths within the voxels in the annular and sector models can be computed geometrically. For annular and sector models, this can be done in a straightforward way by finding the intersection points between the X-ray line and the boundary of an annulus or a sector and computing the lengths between these adjacent intersection points. The path lengths in the combined model Figure 5.1(c) can be computed by evaluating the path lengths using the sector model in Figure 5.1(b) with a “log radius” equal to each of the annulus radii in Figure 5.1(a). Then the path lengths corresponding to each annulus in the combined model are equal to the difference of the path lengths computed using a sector model with the inner and outer annulus radius respectively.

5.2.3 Multi-slice Cone-Beam Path-Length Computation

The geometry shown in Figure 5.1 is appropriate for CT measurements within single cross-sectional slice. This approach is used where X-ray measurements are made using line detectors in a perpendicular plane such as the configuration shown in Figure 2.4(a). Here, to make fuller use of the X-ray data in a cone-beam arrangement, single-slice path length computation needs to be generalized into a multi-slice cone-beam path-length computation. The use of a cone beam creates a more complex 3D geometry within the X-ray fan, causing off-axis rays to pass through multiple adjacent cross-sections. This circumstance couples the calculations between adjacent slices so that they no longer can be analysed separately. Besides the more complicated geometry, this arrangement creates no conceptual change to the measurement, and the CT reconstruction Equation (2-5) still applies. However, this practice greatly expands the use of the available data from the X-ray source, and thus the path length matrix \([G]\) becomes
considerably larger and more computationally intensive to evaluate, but fortunately, with the coarse-resolution models used here, the resulting size is still tractable.

Figure 5.2 Oblique X-rays through the Log Specimen: (a) Perspective view, (b) Side view

Figure 5.2 illustrates the geometry of the cone-beam X-ray configuration, where ray i obliquely passes through the log specimen. To fit 3D cone-beam geometry, a 3D log model is proposed. This model is a generalization of the 2D models, by slicing the logs into many slices containing annular, sector and combined voxels with a thickness defined by the user and each slice is bounded by planes perpendicular to Z direction. In this setup, the X-ray detection surface is a cylindrical surface and each pixel location is known from the cylindrical adjustment introduced in Chapter 4. From the X-ray source to the detector pixel, an X-ray propagation line can be connected that intersects with the log at point C1 and C2 and intersects with several slice boundaries at points such as A and B. The coordinates of C1 and C2 can be computed from a line and cylinder intersection and intersection points A and B can be found by line and plane intersection similarly. Then, for the slice of interest, such as the slice bounded by A and B in
Figure 5.2(b), B can be projected perpendicularly to B' and the voxel path-length can be determined within the perpendicular plane similar to single-slice path-length analysis. The computed voxel path length will then be projected back to the oblique X-ray direction at the end.

Figure 5.3 illustrates the multi-slice voxel path-length diagram within the “standard” log cross-section view. The difference between the single-slice path length diagram (Figure 5.1) and multi-slice path length diagram (Figure 5.3) is that the oblique X-ray comes into the slice at point A and goes out at point B’ instead of passing through the full log. As a result, only voxels interacting with line segment AB’ have existing path lengths. The multi-slice voxel path-length computation is more complex but still can be derived geometrically. In the annular model, the useful voxel radii can be confined in the range of \([d, \max(r_A, r_B)]\), where \(d\) is the log center to X-ray beam distance and \(r_A\) and \(r_B\) are point A and B’ radius. In the sector model, the sector voxels of interest spans the angle of \([\theta_A, \theta_B]\). Then the path lengths within the each voxel can be computed by finding the intersection points between the X-ray line and the boundary of an annulus or a sector of interest and computing the distance between these adjacent points. In the
Combined model, the multi-slice voxel path-length computation follows the same concept as its counterpart in the single-slice case. This can be done by evaluating the path lengths using the sector model in Figure 5.3(b) with a “log radius” equal to each of the annulus radii in Figure 5.3(a). Then the path lengths corresponding to each annulus in the combined model are equal to the difference of the path lengths computed using a sector model with the inner and outer annulus radius respectively.

The computed path-lengths in a perpendicular slice need to be projected back to the inclined X-ray propagation direction. Equation (5-2) determines the inclination of each ray on the cylindrical detector surface.

\[
\alpha = \sin^{-1}\left(\frac{Z_i}{\sqrt{X_i^2 + (Y_i - Y_0)^2 + Z_i^2}}\right)
\]  
(5-2)

where \((X_i, Y_i, Z_i)\) are the pixel coordinates at cylindrical detection surface and \((0, Y_0, 0)\) is the X-ray source coordinate.

Then the inclined path length within each slice can be computed using Equation (5-3):

\[
S_{in}^j = \frac{S_{proj}^j}{\cos(\alpha)}
\]  
(5-3)

where \(S_{in}\) is the inclined path length and \(S_{proj}\) is the projected path length within slice \(j\).

Computing all voxel path lengths in the cone-beam setup within each projection is an intensive process. However, the process can be much simplified by using the scanner symmetric geometry, so only one quarter of the path lengths need be computed, and the others assigned by reflections across the two symmetry axes.
5.3 Path-Length Matrix Formation

5.3.1 Basic Path-length Sub-matrix

Single-slice and multi-slice path-length computation under “standard” log view has been introduced. Placing the computed path-length into the corresponding position yields the basic path-length sub-matrix $G_B$. The rows of $G_B$ matrix correspond to the number of pixel measurement within one projection and columns represent the voxels in which densities will be reconstructed. $G_B$ matrix has element $G_{Bij}$, which is the path length of ray $i$ as it passes through voxel $j$.

![Diagram](image)

Figure 5.4 Single-Slice Basic Path-Length Sub-Matrixes: (a) Annular model, (b) Sector model, (c) Combined model

Figure 5.4 visualizes the single-slice basic path-length sub-matrix $G_{SB}$, where $G_{SBa}$, $G_{SBs}$, $G_{SBC}$ represents separately the sub-matrix for annular, sector and combined models. For annular and sector models, the number of columns are sequenced according to annular, sector index and
in the combine model, columns are first grouped according to the sector arrangement, and then within each sector, voxels are sequenced according to their annular index.

Figure 5.5 Multi-Slice Basic Path-Length Sub-Matrixes: (a) Annular model, (b) Sector model, (c) Combined model

Figure 5.5 visualizes the Multi-slice basic path-length sub-matrix $G_{MB}$, where the $G_{MBa}$, $G_{MBs}$, $G_{MBc}$ are the basic sub-matrixes for annular, sector and combined models. The multi-slice sub-matrix is much larger compared to the single-slice one, where the full 2D X-ray measurement is used and all slices within the X-ray illumination cone appear in the matrix simultaneously. Despite the much greater matrix scale, the multi-slice basic sub-matrix is a direct extension of the single-slice case, where the columns are first divided into different slice-corresponding blocks and then within each slice, the same column sequencing in the single-slice sub-matrix is applied.
5.3.2 Basic Path-length Sub-Matrix vs. Full Path Length Matrix

For each CT log scan, many projections of measurements will be made. Assembly of the sub-matrixes gives the full size path-length $G$ matrix. Equation (5-4) shows the assembly of the matrix $G$:

\[
G = \begin{bmatrix}
G_0 \\
G_1 \\
. \\
. \\
G_{N-1}
\end{bmatrix}
\]

(5-4)

where $G_N$ represents the path-length sub-matrix on the nth projection direction.

Although the coarse-resolution voxel arrangement dramatically reduces $[G]$ matrix size compared to the conventional approach, storing the full $[G]$ matrix is still a very challenging task. For an example of a multi-slice sector full path-length matrix $G_{Ms}$ (56 slices, 36 sectors, 36 projections, 180x128 pixels per projections, double precision), it requires a 6.4GB space to store the full matrix. These matrices will get bigger when using combined geometry model or implementing the spiral-motion test.

The “standard” log view helps to “walk around” this challenge. For a full revolution log scanning, by arranging the number of projections equal to the number of sectors used in the reconstruction model, the log X-ray path-length alignment remains the same at each projection. Only the voxel indices where each X-ray visited are changed by an integer number of sectors due to the rotation. Therefore it is only necessary to store the basic path-length sub-matrix and then to rotate the columns to correspond to the alignment of the subsequent projections.
For the annular model, each voxel is axi-symmetric, so log rotation has no effect on the geometry and the voxel indexing. Thus for different projections, the path-length sub-matrixes keep the same as shown in Equation (5-5):

\[ G_{Sa_n} = G_{Sba} \quad G_{Ma_n} = G_{Mba} \]  

For the sector model, in basic path-length sub-matrix, the change of voxels index is equivalent to the rotation of columns. Therefore, at the nth projection, the sub-matrix \( G_{Sn_n} \) is formed by shifting the columns of the \( G_{Sba} \) to the left \( n \) times. In a multi-slice reconstruction, sub-matrix \( G_{Msn_n} \), can be obtained by similar column rotation within each slice-block.

\[ G_{Sa_n} = \text{circshift} \ (G_{Sba}, n) \quad G_{Ma_n} = \text{blockcircshift} \ (G_{Mba}, n) \]  

where \( \text{circshift}() \) operator represents the matrix columns shift operation and \( \text{blockcircshift}() \) operator represents the matrix columns shift operation within pre-define slice corresponding blocks.

For the combined model, the sub-matrix acquisition is very similar to the sector model analysis. In this model, each sector is divided into smaller voxels by the predefined annuli. Thus per sector log rotation, all \( m \) combined voxels within that sector rotates simultaneously and then the amount of column rotation is multiplied by the number of annuli involved. Equation (5-7) gives the formula to form \( G_{Sc_n} \) and \( G_{Mc_n} \) from \( G_{Sbc_c}, G_{Mc_c} \).

\[ G_{Sc_n} = \text{circshift} \ (G_{Sbc_c}, m \times n) \quad G_{Mc_n} = \text{blockcircshift} \ (G_{Mc_c}, m \times n) \]  

5.4 Density Computation General Procedures

The path length matrix formation and basis weight data normalization provide \([G]\) and \(\{d\}\) in Equation (2-5). To be more specific, single-slice matrix-vector linear systems are:

\[ [G_{Sa}]{\{\rho\}} = \{d_{BW}^S\} \quad [G_{Sc}]{\{\rho\}} = \{d_{BW}^S\} \quad [G_{Sc}]{\{\rho\}} = \{d_{BW}^S\} \]  

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where $G_{Sa}$, $G_{Ss}$, $G_{Sc}$ separately represents single-slice annular, sector, combined geometry full path-length matrices and $d_{BW}^s$ is the single-slice basis weight data vector.

Cone-beam multi-slice matrix-vector linear systems are:

$$
[M_{BWM_a} d_{G}] = \rho \quad ; \quad [M_{BWM_s} d_{G}] = \rho \quad ; \quad [M_{BWM_c} d_{G}] = \rho \quad (5-9)
$$

where $G_{Ma}$, $G_{Ms}$, $G_{Mc}$ separately represents cone-beam multi-slice annular, sector and combined geometry full path-length matrices and $d_{BW}^M$ is the corresponding basis weight data vector.

### 5.4.1 Least-Squares Approach

In conventional CT practice, the massive size of $[G]$ requires the use of indirect inverse solution methods. Here, the number of voxels is much smaller and so a direct solution of Equation (2-5) is feasible. The resulting highly over-determined Equation (2-5) can be solved in a least-squares sense as:

$$
$$

where matrix $[G]^T [G]$ is square with row/column size equal to the number of voxels, which is a moderate size number compared with the number of pixels used in all the projections.

### 5.4.2 $[G]^T [G]$ Direct Computation

For convenience, $[G]^T [G]$ is renamed as resultant matrix $[A]$ and $[G]^T \{d\}$ as converted basis weight vector $\{b\}$, thus Equation (5-10) becomes Equation (5-11):

$$
[A] \{\rho\} = \{b\} \quad (5-11)
$$

The proposed density reconstruction uses the same set of X-ray measurement data for all reconstruction geometries. To be more specific, there are single-slice annular, sector and combined resultant matrices $A_{Sa}$, $A_{Ss}$, $A_{Sc}$ and converted basis weight vectors $b_{Sa}$, $b_{Ss}$, $b_{Sc}$;
similarly multi-slice annular, sector and combined resultant matrices $A_{Ma}$, $A_{Ms}$, $A_{Mc}$ and converted basis weight vectors $b_{Ma}$, $b_{Ms}$, $b_{Mc}$.

Section 5.3.2 describes how basic path-length sub-matrix preserves all the information in the full path-length matrix. Thus $[A]$ matrix and $\{b\}$ vector can be much more efficiently computed from the basic path-length sub-matrix instead of the direct operation on $[G]^T[G]$. Matrix $[A]$ is symmetric positive-definite matrix and at most half of its elements need to be calculated. For single-slice annular and sector models, the computations are done on the column multiplication phase. For single-slice combined model and multi-slice models, both of the basic path-length sub-matrixes and resultant $[A]$ matrixes are first divided into sector or slice corresponding blocks and then $[A]$ is formulated block by block based on block matrix multiplication. Figure 5.4 and 5.5 illustrate the block structure in the basic path-length sub-matrix. Equation (5-12) to Equation (5-23) shows the formulas which implement the direct computation process.

For single-slice annular model,

$$A_{Sa}(i, j) = n \times G_{Sba}(i)^T G_{Sba}(j)$$  \hspace{1cm} (5-12) \\

$$b_{Sa}(i) = \sum_{l=0}^{l=n} G_{Sba}(i)^T d(l)$$  \hspace{1cm} (5-13)

For single-slice sector model,

$$A_{Ss}(i, j) = \sum_{l=j;j \neq i, k \neq n; k < l+n, k = k-n; k = l+1} G_{Sbs}(k)^T G_{Sbs}(l)$$  \hspace{1cm} (5-14) \\

$$b_{Ss}(i) = \sum_{l=0;k = i} G_{Sbs}(k)^T d(l)$$  \hspace{1cm} (5-15)

For single-slice combined model,
\begin{align}
A_{Sc}(i, j)_{m\times n} &= \sum_{l=j; k=i}^{l=n-1; k=n} [G_{SBc}(k)]_T^{m \times p} [G_{SBc}(l)]_{p \times m} \\
(5-16) \\

b_{Sc}(i)_{m \times 1} &= \sum_{l=0, k=i}^{l=n-1; k=n} [G_{SBc}(k)]_T^{m \times p} d(l) \\
(5-17) \\

\text{For multi-slice annular model,} \\
A_{Ma}(i, j)_{m\times n} &= n \times [G_{MBA}(i)]_T^{m \times p} [G_{MBA}(j)]_{p \times m} \\
(5-18) \\
b_{Ma}(i)_{m \times 1} &= \sum_{q=0}^{q=n} [G_{MBA}(i)]_T^{m \times p} d(q) \\
(5-19) \\

\text{For multi-slice sector model,} \\
A_{Ms}(i, j)_{n\times m} &= \sum_{q=0}^{q=n} [G_{MBs}^q(i)]_T^{n \times p} [G_{MBs}^q(j)]_{p \times n} \\
(5-20) \\
b_{Ms}(i)_{n \times 1} &= \sum_{q=0}^{q=n} [G_{MBs}^q(i)]_T^{n \times p} d(q) \\
(5-21) \\

\text{For multi-slice combined model,} \\
A_{Mc}(i, j)_{(n\times m)(n\times m)} &= \sum_{q=0}^{q=n} [G_{MBc}^q(i)]_T^{(n \times m) \times p} [G_{MBc}^q(j)]_{p \times (n \times m)} \\
(5-22) \\
b_{Mc}(i)_{(n\times m) \times 1} &= \sum_{q=0}^{q=n} [G_{MBc}^q(i)]_T^{(n \times m) \times p} d(q) \\
(5-23) \\
\end{align}

where \( n \) is the total number of sectors, \( m \) is the total number of annuli; \( s \) is the total number of slices within the cone beam; \( p \) is the number of data measurement within each projection; \( G_{SBa}(i) \) is the \( i \)-th column of the basic single-slice annular path-length sub-matrix; \( G_{SBs}(i) \) is the \( i \)-th column of the basic single-slice sector path-length sub-matrix; \( [G_{SBc}(i)] \) represents the annuli block matrix with respect to \( i \)-th sector in the basic single-slice combined path-length sub-matrix; \( [G_{MBA}(i)], [G_{MBs}(i)], [G_{MBc}(i)] \) represent the block matrixes with respect to \( i \)-th slice in...
the basic multi-slice annular, sector and combined path-length sub-matrix separately; d(i)
represents the basis weight data corresponding to ith projection.

Directly formulating [G]T[G] is computationally intensive process. Care has been taken
into studying the structure of the resultant matrix. For single-slice reconstruction, the column
rotation phenomenon makes A_{Ss} a teoplitz matrix and A_{Sc} a block-teoplitz matrix [74]. Thus
only the first row or row of blocks needs to be computed. For multi-slice reconstruction, an
oblique X-ray can maximum pass a fixed number of slices (maximum 6 slices for the proposed
scanner setup). Thus A_{M(i,j)} is block band-width matrix, any components beyond the primary
band-width can be automatically set to zero.

5.4.3 Density Solution

Once the resultant matrix [A] and converted basis weight vector \{b\} are computed, the
Equation (5-11) can be solved using a Cholesky solver [75]. Then the density inverse
computation includes: Cholesky decomposition (factorization) in Equation (5-23) and forward
/backward substitution in Equation (5-24).

\[
[ A ] = [ L ][ L ]^T 
\]  \hspace{1cm} (5-23)

where L is a lower triangular matrix with real and positive diagonal entries.

Forward and backward substitution to solve density vector \{ρ\}:

\[
[L] \{ y \} = \{ b \} \hspace{1cm} [L]^T \{ ρ \} = y
\]  \hspace{1cm} (5-24)

GNU scientific library (C/C++) [76] is used to implement the Cholesky decomposition
and density inverse computation. In the proposed log CT inversion, the most time consuming
part is to compute and factorize the matrix [A]. However, by the “standard” log view approach,
the path length matrix need be computed and factorized only once. The factorized matrix [L] is
stored instead, and recalled for use with different logs. Thus, the computation time of matrix [A] and density inversion is not an issue for real-time log scanning.

5.5 Conclusion

The CT log reconstruction mathematics and procedures are introduced in this chapter. Single-slice and multi-slice voxel path-length computation provides the foundation of making basic path-length sub-matrixes. The “standard” log concept makes possible the reuse of the basic sub-matrixes to avoid computing and storing the full path-length matrix [G] explicitly. A least-squares inversion approach is taken to solve the linear system. Both [G]T[G] and [G]T{d} are computed directly by using basic path-length sub-matrix and basis weight vector. Finally, a Cholesky solver is applied to calculate the voxel densities.

The proposed CT log reconstruction has the following advantages: 1. Annular/sector/combined reconstructions share the same basis weight data set. Reconstruction using different models can be done separately or simultaneously depending on the log condition and features looked for. 2. The path length matrix is predetermined and can be scaled to fit different size logs. This scaling is not perfect because change in log diameter changes the angles within the scanned volume in a slightly non-linear way. However, for the small angles used here (16° X-ray cone angle in current setup), the non-linearities are modest. This feature will have to be tested in practice. At worst, predetermined path length matrices [A] will be needed for a compact sequence of different log diameters to accommodate large changes in log size.

This chapter covers single-slice and multi-slice cone-beam reconstruction. The multi-slice spiral-motion reconstruction is beyond the scope of this thesis. The spiral-motion scanning shares the same basics as the cone-beam multi-slice reconstruction. They have exactly the same basic path-length sub-matrices. When spiral-motion scanning is applied, computation burden is
even greater since the whole log needs to be reconstructed simultaneously. Fortunately, the coarseness and symmetry of the proposed CT reconstruction arrangement keeps the size of the calculation moderate. The computation methodology on spiral-motion log scanning will be explored and designed in future work.
Chapter 6: Log Scanning Test Demonstration and Result Validation

6.1 Overview

The proposed coarse-resolution CT scanning system’s hardware design, data processing and CT reconstruction have been elaborated in Chapters 3, 4 and 5. The proposed approach is highly tailored to log scanning and is designed to achieve log feature identification in a simple, practical and efficient way. Sample log scanning tests have been conducted to validate the effectiveness of the proposed system, and successful coarse-resolution reconstruction has been realized. This chapter will focus on presenting the experimental test results. It will briefly introduce the scanning experiment and data acquisition/reconstruction software, present both X-ray and computed basis weight data, and then demonstrate sample log single-slice/multi-slice reconstruction results. These results will be compared with cross-sectional reconstructions using the same measurements with a conventional filter-back-projection algorithm [77]. The effectiveness and advantages of the “coarse-resolution” reconstruction will be demonstrated using examples. The good scanning performance achieved gives confidence in the usefulness and applicability of the proposed approach to practical log scanning in sawmills.

6.2 Log Sample, Test Description and Scanning Software

6.2.1 Log Sample and Test Description

A group of log samples was provided by FPInnovations to implement the scanning test. All samples initially were obtained as newly harvested log sections (wet), but are substantially dried due to the lab environment compared to their initial state. This makes the scanning task a bit easier as dry logs tend to have more density contrast between features. The sample log used in the pilot CT scanning test is of amabilis fir (abies amabilis), with 23 annual growth rings, a 34cm average section diameter, 90cm length and 28.5kg weight. Figure 6.1 recaps Figure 3.9(b),
demonstrating the CT log scanning system which has been set up at Research Pavilion at Vancouver General Hospital. Detailed equipment descriptions were explained in Chapter 3. The scanning tests have been implemented according to UBC Radiation Safety Procedures [78] and equipment has been approved for safe operation by Radiology Matrix Consulting Ltd [65].

Figure 6.1 CT Log Scanner Setup (recap)

A 100kVp (peak voltage) and 5mA (normal current) setting is used to image the sample log. This setting was selected by analyzing the still log X-ray image for best combination of brightness and contrast. During each scanning test, a group of X-ray images were taken at equal rotational intervals, each with a fixed exposure time (1s, 100ms, 10ms) at a different rotation speed (20s/rev, 8s/rev, 2.5s/rev). To achieve the sector boundary trigger design, the number of images taken is selected equal to the number of sectors in the CT models. The same set of X-ray measurements was used for each of the voxel model choices.
6.2.2 X-Log Studio Software Demonstration

Figure 6.2 “X-Log Studio”: Coarse-Resolution CT Log Scanner Control and Reconstruction Software

The proposed log scanning approach is a highly integrated test. To fulfill the scanning task, a unified log scanner control and reconstruction software “X-Log Studio” was developed using Visual Studio 2008 (C/C++) by the author. Figure 6.2 shows the graphical interface of this software. This multi-task software can be used in real-time scanning control/reconstruction and off-line data analysis. This software functions as the “brain” of this project. It controls all equipment and implements the control logic introduced in Chapter 3, achieves accurate data acquisition and processing designed in Chapter 4 and realizes CT density computation elaborated in Chapter 5. All presented data and reconstruction results in this chapter are obtained and computed using X-Log Studio.
6.3 Log Scanning Raw Data Demonstration

To validate the scanner functionality, log scanning tests were implemented under three different modes: linear scanning, rotation scanning and spiral scanning. Linear scanning requires only translating the log during the imaging process. This is similar to radiography, and provides a projection view of the scanned object. Rotation scanning requires rotating the sample log and acquiring the measurement at controlled rotation intervals. This mode provides the raw data for the proposed single-slice and multi-slice cone-beam reconstruction in this thesis. Spiral scanning is a combination of the linear and rotation one. The log is advanced into a spiral trajectory during scanning.

Figures 6.3-6.5 show example 2-dimensional X-ray images that were obtained from these tests. In these images, the dark areas indicate high X-ray absorption, inferring a higher density on the X-ray path and the bright areas indicate low X-ray absorption, inferring a low density on the path. The centre dark region is the projection view of the sample log and the white background region is unattenuated X-ray beam. Notice that the four corners of the image are darkened, indicating the boundaries of the X-ray cone beam.

6.3.1 Linear Scanning Demonstration

![Figures 6.3 Imaging Log Linear Motion: (a) Beginning-section, (b) Mid-section, (c) End-section](image)
Figure 6.3 shows a series of images from linear scanning. The beginning, middle and end session of the sample log were imaged in this example. The darker regions appearing within the log boundary are knots, which have an elevated density. The sample images in Figure 6.3 reveal a cluster of knots at the beginning section, some small knots scattered within the middle part and another cluster of knots in the ending section. Linear scanning contains substantial information (knot cluster position, etc.) but the projection view makes it very difficult to identify individual features. From a pure X-ray scanning point of view, the proposed scanning system has advantages over the prevailing line-scan camera based X-ray log scanning, which have been introduced to the sawmill industry for some years. The large-format detection has a much better X-ray detection efficiency and scanning a full length log only requires a few snapshots other than letting X-ray run continuously as the log is passing by. Therefore it greatly reduces the radiation safety concerns and the shielding needed in an industrial environment.

6.3.2 Pure-Rotation Scanning Demonstration

![Figure 6.4 Imaging Log Rotation: (a) 60° position, (b) 120° position, (c) 180° position](image)

Figure 6.4 demonstrates a series of raw X-ray measurements from rotation scanning. As the log rotates for one revolution, a group of such images are recorded. The three images are taken at rotation angles: 60°, 120° and 180°. The dark areas in the center correspond to the high
density of a cluster of four approximately equally spaced knots. Smaller nearby knots appear as smaller dark areas on each side. The horizontal bright line in Figure 6.4(a) corresponds to a deep radial crack caused by log drying in the lab environment. View (a) is taken looking directly into the crack, so the crack appears very prominently, while views (b) and (c) are oblique views and therefore do not clearly show the crack. The rotation scanning offers a multi-directional view of the sample log.

6.3.3 Spiral-Motion Scanning Demonstration (For Future Analysis)

Figure 6.5 Imaging Log Spiral-Motion: (a) 0° rotation, (b) 120° rotation, (c) 240° rotation

Figure 6.5 displays the X-ray measurement under spiral-motion imaging. View (a), (b) and (c) are taken at 120° apart, with linear movement of 11.5cm between each. It can be observed that the same cluster of knots rotates and advances as the log passing by the three imaging positions. Similar to rotation scanning, the spiral scanning also offers a multi-directional view of the sample log. The development of multi-slice spiral-motion CT reconstruction is beyond the scope of this thesis, but the rich information in these measurement points the author towards a clear future research direction.
6.4 CT log Scanning Data Processing Demonstration

Raw X-ray measurements must be processed before computing the CT reconstruction. Chapter 4 introduced the data processing design. The major work includes: barrel correction, cylindrical adjustment and basis weight data normalization.

6.4.1 Barrel Correction and Cylindrical Adjustment

Figure 6.6 CT Data Processing: (a) Converted CT Log Data, (b) Barrel Distortion Correction, (c) Cylindrical Adjustment

Figure 6.6(a) shows the converted CT log data (after taking the negative logarithm of the X-ray attenuation ratio) computed from the raw X-ray image in Figure 6.4(a). Similar to raw X-ray images, the CT data image has a curved outer log boundary due to a barrel distortion from the wide-angle lens used in the detector. Figure 6.6 (b) shows the barrel-corrected data. In the image, the barrel distortion is removed, the curved boundary is corrected and all features return to their true shapes. Figure 6.6(c) shows the CT data after applying cylindrical adjustment. It is hard to notice the subtle difference made by cylindrical adjustment due to the relatively small X-ray cone angle (approximately 16º).
6.4.2 Basis Weight Data Demonstration

Figure 6.7 demonstrate a series of basis weight data images by applying the proposed basis weight normalization to the CT data. This series of images follows the same sequence in Figure 6.4 but with an inverted black and white colour, where knots appears in the bright colour, cracks appears in the dark colour. Basis weight normalization estimate the log “diameters” from CT data images and normalized them as they have the same “standard” diameter.

![Basis Weight Normalization](image)

**Figure 6.7 Basis Weight Normalization:** (a) 60° position, (b) 120° position, (c) 180° position

Another informative way to visualize the X-ray basis weight data is to form a sinogram, which comprises a sequence of the X-ray projections taken within a full log rotation. Figure 6.8 shows the sinogram of 72 projections (every 5° apart) of the cross-section containing the central bright region in Figure 6.7. Each of the four knots within the cross-section creates a light spiral path and the large radial crack creates a dark spiral path.

For single-slice reconstruction, the sinogram basis weight data is all that is needed for inverse density computation. For multi-slice cone-beam reconstruction, a set of basis weight images and all pixels within each image are used and arranged into vector format for inverse density computation.
6.5 Reconstruction Results Demonstration

Both single-slice and multi-slice cone-beam reconstruction have been realized by applying the path-length matrix formulation and inverse density computation procedures described in Chapter 5. CT reconstruction results demonstrated in this section use an 18-annuli annular model, a 36-sector sector model and a 36 sectors with 18 annuli combined model with 1s exposure time X-ray measurement data.

6.5.1 Single-Slice Reconstruction Results

A single-slice inversion study is the initial step to investigate the CT reconstruction characteristics. A single column of pixels was extracted from the center of each of the set of 36 basis weight images exemplified in Figure 6.7, forming a coarse version of Figure 6.8 with 36 projections. These single columns of pixels also simulate the data that would be measured from a conventional line-detector system.
Figure 6.9 Single-Slice Log CT Reconstruction Results: (a) Reconstruction using 18 annuli, (b) Reconstruction using 36 sectors, (c) Reconstruction using 18 annuli x 36 sectors, (d) Reconstruction using 36 filtered back projections.

Figure 6.9(a) shows the CT reconstruction created using a purely annular model. There are 18 annular voxels with radial boundaries at square root of regular intervals of the log radius. This sequence is chosen so that all annuli have the same cross-sectional area and thus have approximately equal measurement accuracy. This annular arrangement can effectively model axisymmetric features; the bright periphery in Figure 6.9(a) indicates the high material density of the bark of the log. Angularly arranged features such as knots are not displayed in this view.
The sector-shaped reconstruction shown in Figure 6.9 (b), computed using the same data set, has the opposite characteristics. It clearly indicates the cluster of four knots as bright sectors, and the deep crack as a dark sector. However, the bark presence is not indicated. The combined model shown in Figure 6.9 (c), using 18 annuli and 36 sectors, shows the bark and the knot/crack features, but at the expense of greater reconstruction noise.

For comparison, Figure 6.9 (d) shows the filtered back-projection result using the same basis weight data set as the previous three geometrical models. The bark, knot and crack features are also visible in the reconstruction, but with substantial noise, causing the contrast to become quite low. In addition, substantial artifacts are created in the area around the outside of the log where no material density exists.

![Figure 6.10 Log Cross-Section Density Plot: (a) Annular density distribution, (b) Sector density distribution](image)

The character of the results in Figure 6.9 can be explored in more detail by representing the results in graphical form. Figure 6.10(a) shows a plot of the reconstructed density profile along a log radius for the annular results shown in Figure 6.9(a). A steadily increasing density trend can be observed, which is common among many tree species [79]. In this particular log,
the higher density around the perimeter corresponds to the bark on the log. The corresponding high density narrow ring can also be observed in Figure 6.9 (c) and (d). Figure 6.10(b) shows a plot of the reconstructed density profile around the log circumference for sector results in Figure 6.9 (b). In this graph, the knots observed in Figure 6.9 (b) appear as four sharp peaks and the crack appears as a sharp valley. This graph has circular continuity so that the right side joins back to the left. The graph shows the average density of the log is about 0.38g/cm³, with the knot area density 0.46g/cm³ about 21% higher than the average. Based on the measured weight of the test log = 28.5kg, average diameter = 34cm, length = 90cm, the average density was determined gravimetrically to be 0.36g/cm³, compared well with the reconstruction result.

A very important characteristic of the coarse-resolution reconstruction approach is that it requires few projection measurements (less data acquisition burden) and produces reconstructions that are much more robust and noise immune than those from conventional procedures. To illustrate these characteristics, scanning tests of the same sample log were done using different measurement parameters (72 projections with 1s exposure, 36 projections with 1s exposure and 36 projections with 100ms exposure). The reduction in number of projections cuts the measurements quantities in half and the reduction in exposure time reduces the X-ray measurement quality by the presence of substantial shot noise. Figure 6.11 compares the results of the conventional filter-back-reconstruction and the proposed sector reconstruction using the same data set. Figure 6.11 (a), (b) and (c) show how the conventional filtered back-projection results deteriorate when reducing measurement projections and applying lower quality data. The much-increased noise within the log and the artifacts outside the log are very evident and the dominant features became indistinguishable. An enlargement of conventional voxel size for Figure 6.11 (b) and (c) would reduce noise but would also reduce the already very faint contrast
between high and low density material. The sector reconstruction results in Figures 6.11 (d), (e) and (f) show a much more stable response. The effect of using voxel geometry that mimics the log feature geometry is to guide the CT reconstruction and to average the noise in a way that emphasizes the features rather than smooth them out. Despite Figure 6.11 (d) composes 72 sectors, all three figures clearly identify the dominant features: four knots and crack and proves a much greater tolerance on the quantity and the quality of the input data.

Figure 6.11 Comparison between Filtered-Back-Projection (FBP) and Sector Reconstruction (SR):
(a) FBP with 72 projections (1s exposure), (b) FBP with 36 projections (1s exposure), (c) FBP with 36 projections (100ms exposure), (d) SR with 72 projections (1s exposure), (e) SR with 36 projections (1s exposure), (f) SR with 36 projections (100ms exposure)
Figure 6.12 Basis Weight Calibration on Reconstructed Density: (a) Annular density reconstruction comparison, (b) Sector density reconstruction comparison

Basis weight calibration is introduced as a standard step of data processing in Chapter 4 and its effectiveness needs to be examined. Figure 6.12 compares the annular and sector density reconstruction results between using the basis-weight calibration and using an estimated constant scaling. It can be observed that with basis-weight correction, the annular reconstruction tends to yield a smoother distribution and the sector reconstruction reflects a higher density contrast between knotty and normal material. This result shows the effectiveness of the calibration because it corrects the nonlinearity in the data due to the beam-hardening effect when X-ray penetrating denser material or through great path length, recovering the true density distribution and making knots area more distinguishable.

6.5.2 Multi-Slice Cone-Beam Reconstruction Results

The single-slice reconstruction results are interesting because they provide useful comparisons with conventional practice using line-detector measurements. Cone-beam X-ray measurements provide a full field of data, so it is possible to reconstruct multiple parallel cross-sectional slices simultaneously from X-ray measurements within a full 360° rotation. In multi-
slice reconstruction, the slice thickness (about 0.95cm) is chosen to equal the distance which the scanner moves per sector rotation in spiral-motion mode. The X-ray cone covers a total of 56 slices under the scanning geometry. Reconstruction using the annular model with 18 annuli and sector mode with 36 sectors are demonstrated in this section.

Figure 6.13 Multi-Slice Reconstruction: (a) Annular model (slice No.10), (b) Annular model (slice No.25), (c) Annular model (slice No.40), (d) Sector model (slice No.10), (e) Sector model (slice No.25), (f) Sector model (slice No.40).

Figure 6.13 shows the multi-slice annular and sector results obtained at three slice positions (slice No. 10, 25, 40) from the same data set as used for Figures 6.9 and 6.10, but using the entire basis-weight images, not just the central column. Annular reconstructions in these
three slices demonstrate a consistent density distribution trend as observed before: a high density bark region and a low density interior. Three sector reconstructions in Figure 6.13 (d-e-f) do not look very alike, but they all successfully identify the deep radial crack in the correct position. Slice No.25 corresponds to the same cross-section in single-slice reconstruction. Therefore, annular and sector results in Figure 6.13 (b) and (e) looks almost identical to Figure 6.9 (a) and (b). The consistent density distribution and correct feature identification proves the functionality and stability of multi-slice computation.

Another effective way to analyze the reconstruction result is to view all slices together and form a longitudinal density display. Figure 6.14 shows such plots illustrating the variation of log longitudinal densities along the radial direction (annuli) or around the circumference (sectors). In the cone-beam scanning, the first and last 5 slices are partially scanned due to the cone-beam geometry, therefore they are truncated from the display. Figure 6.14(a) shows the longitudinal annular density plot, which is named a “quarter-sawn board” plot because it is conceptually equivalent to a radiograph of a quarter-sawn board. (“Quarter-sawing” is done by

![Figure 6.14 Log Longitudinal Density Profile: (a) Annular “quarter-sawn board” plot, (b) Sector “veneer” plot](image-url)
quartering a log length-wise first and then cutting the boards so as to obtain annual rings mostly perpendicular to their face [69].) To facilitate interpretation, a mirror image of the annular reconstruction has been added to represent a double-width board spanning the entire log diameter. Figure 6.14(a) clearly demonstrates overall log features within the whole log section: the high-density region at the bark and the adjacent lower density interior region. It can be observed that the knotty areas cause some disturbances to the annular reconstructions, but the features and overall distribution are not affected at all. Figure 6.14(b) shows the longitudinal sector density plot, which is named a “veneer” plot because it corresponds to the pattern that would be seen if a veneer sheet were cut from the outside of the log. (Rotary veneer cutting is done using a large machine tool that peels the outside of a log in much the same way that a pencil sharpener cuts a pencil [69]. The cut is parallel to the outside cylindrical surface rather than conical, thus producing a rectangular veneer sheet.) The veneer plot in Figure 6.14(b) clearly shows the radial crack (horizontal dark line) and the four prominent knots (bright area in the middle) vertically at the center, with two much smaller knots (two bright areas close to the right) appearing on the right side. Such knot patterns are very typically seen in rotary cut veneers.

Multi-slice reconstruction also enables the log density distribution to be displayed in graphical form. Figure 6.15(a) shows the average annular density for the whole log section. The average annular density plot demonstrates a much smoother trend of radial density distribution and gives a reliable quantitative estimation of ring density. Figure 6.15 (b) shows the average sector density within the parallel slices. The graph prominently shows the locally elevated wood density caused by the presence of the central knot cluster. The two small knots on the right
produce a much smaller average density peak. These average density peaks provide a simple method for identifying the location of knot clusters.

Figure 6.15 Average Density Plot: (a) Radial average annular densities, (b) Longitudinal average sector densities

6.6 Conclusion

Coarse-resolution log scanning tests, X-ray measurements, data processing and reconstruction results have also been presented. Both single-slice and multi-slice cone-beam reconstruction results compare well with the results from conventional filtered-back-projection method. Successful X-ray measurement under different log motions validates the log scanner’s hardware design in Chapter 3; non-ideal X-ray quality tolerance and basis weight data formation prove the effectiveness of novel processing technique in Chapter 4; good reconstruction results validate computation implementation in Chapter 5.

It is demonstrated by the reconstruction results that the geometry-based coarse-resolution models give a good representation of log internal features. These models fix in advance either that the log features are axisymmetric or that any knots start at the center and radiate towards the perimeter as a sector shape. Features such as cylindrical geometry can be “assumed” rather than
painstakingly computed. These advance specifications have the effect of guiding the CT reconstruction towards physically realistic results that require almost no segmentation to analyze the results. The sector, annular and combined voxel arrangement contains shape and position information, thus are already “pre-segmented”. The proposed coarse-resolution log density approach also tolerates the input data of modest quality and quantity, thus making it attractive and applicable in real-time log scanning, where speed is of great concern and measurement quality cannot be guaranteed.

Based on the good scanning performance and results validation, the coarse-resolution CT log scanning approach proposed in this thesis is shown to be effective. It opens new opportunities to the practical CT saw-log scanning for sorting and grading application.
Chapter 7: Conclusion and Future Research

7.1 Discussion

A novel geometry-based coarse-resolution CT log scanning technique has been designed and implemented in this research. The approach proposed is highly tailored to a specific application: log scanning. Most research in this field has either focused on applying existing CT technology or using advanced data analysis/image processing techniques for feature identification inside the log. This is the first research on designing and customizing an entire CT system (hardware, data processing, algorithm, control and reconstruction software, etc.) and delivering a prototype scanner for concept demonstration. The present design uses a stationary X-ray source and a customized large-format detector as stand-alone equipment, thus making them convenient to integrate with current transportation setup in a sawmill. The coarse-resolution feature-specific geometrical models substantially and fundamentally influence the CT reconstruction. The models specify in advance either that the log features are axisymmetric or that any knots start at the center and radiate towards the perimeter as a sector shape. The geometric resemblance of the models to the physical features of the logs guides the inversion towards realistic results and stabilizes the solutions against the noise in the X-ray measurement.

In conventional CT reconstructions, rigid body motions are very damaging and so highly accurate mechanical systems are required, usually involving controlling and synchronizing the motion of the X-ray source and detector system. “Lagrangian” CT data processing references CT reconstruction to the log other than to a fixed space. The “standard” log view, the basis weight re-centering and normalization enable the CT inversion to tolerate small rigid body motions and reuse the pre-computed path length matrix. In such case, no special care needs to be taken to
mount the log specimen exactly along the rotation axis of the transport system, which simplifies the preparation work and complexity.

7.2 Conclusion

The novel coarse-resolution scanning concept, the geometry-based log models, “standard” log view design, “Lagrangian” data processing and efficient reconstruction algorithm form the cores of the research work. The scanning approach proposed in this thesis has several advantages over conventional approaches:

1. It reduces scanner mechanical complexity by using a stationary X-ray source and detector while generating needed scanning trajectory on the measured object.
2. It uses relatively straightforward equipment whose robustness and cost are appropriate for sawmill use.
3. It uses feature-specific voxel geometries to guide and stabilize the CT reconstruction.
4. It reduces the number of features that need to be determined, thus reducing the scale of computation.
5. It computes voxel densities only within the log, without wasting outside-log computations as in conventional CT reconstruction.
6. It implements “Lagrangian” data processing method and compensates for rigid-body-motions and log ellipticity.
7. It is noise-robust and requires fewer X-ray projections, thus reducing the effort on data acquisition.
8. It uses the large-format detector, thus making scanning big diameter logs possible.
9. It achieves cone-beam multi-slice CT reconstruction, thus greatly increasing the scanning speed.
The coarse-resolution reconstruction results compare well with results from conventional CT approach. The availability of the location and size of internal features provide rich information to determine the grade of input logs and to optimize subsequent processing to maximize the yield of high-quality products. The promising scanning results give confidence in the usefulness and applicability of the proposed methodology to practical log scanning in sawmills.

7.3 Limitations

The ongoing coarse-resolution log scanning research has its limitations. First, it can measure log diameter only approximately, thus cannot identify exact physical dimensions directly. Enabling the CT inversion to be done in a “standard” normalized form has a great mathematical convenience. However, the results ultimately need to be referenced to the actual log diameter to identify physical features. The X-ray measurements do provide an approximate indication of the physical dimensions, but the presence of radial rigid-body motions within a cone-beam geometry change the size of the scanned log image and therefore impede precise identification of dimensions. One practical solution is to use an added optical scanner to identify log size and position. Such optical scanners are widely used in the wood industry and are rugged and relatively inexpensive. The effectiveness of combining CT and optical scanning needs to be examined.

Second, the proposed method relies on log a-priori information: the circular geometry, the annular clear wood structures and the sector shaped knots. Logs are natural resources and geometry varies among the specimen. For logs that have highly irregular shapes, the proposed CT scanning will not produce satisfactory results. Additionally, the proposed CT models assume target features exist in the perpendicular plane and all voxels represents the average density in
the annular, sector or combined voxel. For some log species, the branches grow at a conical angle from the perpendicular cross-section. In such case, the knots pass through several cross-sections, leaving only part of the knots in each one. Combined voxel should be able to identify the conical knots at certain extent, but the reduced contrast between knotty materials and clear wood makes the identification a challenging task. One possible supplement is to use CT models with conical voxels instead of perpendicular voxels. This scheme will be designed and tested in future.

Third, the quality of the X-ray measurement obtained from the prototype system is much lower than those from medical CT equipment. For ultra-fast scanning, the detector exposure time has to be reduced dramatically, thus degrading the measurement quality (shot noise). The equipment developed here can complete a scanning test at 40cm/s with an exposure time at 10ms. With the present apparatus, measurements below 10ms become too noisy for CT computation. This issue can be resolved by the use of flat-panel X-ray detectors. These are presently available for medical use in relatively small sizes and very high spatial resolution, and are very costly. In future it may be expected that more appropriate larger size panels with more modest spatial resolution and lower cost will become commercially available.

Fourth, the prototype scanner as an idea-proofing tool cannot be applied directly to industrial application. Sawmill environment differs greatly from the controlled laboratory environment. Generating controlled spiral-motion on heavy and rapidly moving logs in sawmill is a challenging task. Ideally, logs should be put into spiral-motion during the transportation phase without delaying the manufacturing process. Novel machinery and mechanism need to be designed for this purpose.
7.4 Future Research Direction

Future research will continue on further evaluating the proposed methodology and exploring new methods to utilize the log scanning data and improving scanning result. Research work includes:

1. Complete the multi-slice spiral-motion reconstruction algorithm design and implementation. This part of work is a direct extension of the current research and is expected to be finished in future.

2. Explore the effectiveness of the proposed approach on large-scale rigid-body motion. Theoretically the “Lagrangian” data processing and normalization can minimize the rigid body motion effect, but its effectiveness on large-scale rigid body motion needs to be examined. To achieve this, the log will be installed off rotation center with an increased distance to simulate the excessive motion. CT reconstruction results will be then analyzed for evaluation.

3. Implement “green” (newly harvested with high moisture content) log scanning test and evaluate the performances. “Green” logs are much denser than dry logs, thus requiring using higher power X-rays. Most of saw-logs are “green”, therefore the results from this series of tests can be more realistic and representative.

4. Design conical voxel reconstruction algorithm and evaluate the performance. Conical voxel reconstruction can dramatically increase the detection sensitivity towards to the knots growing at an angle from the perpendicular direction. This offers a novel method using existing scanning data and expends the proposed system’s applicability to a wider range of log species.
5. Investigate applying the proposed log scanning approach to real sawmill operation. This part of work will include integrating the current scanner setup to sawmill production line and designing novel mechanisms and machinery to realize log spiral-motion. Real sawmill scanning tests will be planned in future.
**Bibliography**


