A Computer Vision System for Lumber Production Planning

Suchendra M. Bhandarkar
Department of Computer Science
The University of Georgia
Athens, GA 30602–7404, U.S.A.
suchi@cs.uga.edu

Timothy D. Faust and **Mengjin Tang**
Warnell School of Forest Resources
The University of Georgia
Athens, GA 30602–2152, U.S.A.
tfaust@uga.cc.uga.edu, tang@uga.cc.uga.edu

Abstract

A computer vision-based system for lumber production planning is described. Computer axial tomography (CT or CAT) images of hardwood logs are analyzed for identification and classification of internal log defects. Individual CT image slices are analyzed for detection of 2-D defects which are correlated across CT image slices in order to establish 3-D support and identify true 3-D defects. Currently, the system is capable of 3-D reconstruction and rendering of the log and its internal defects from the individual CT image slices. It is also capable of simulation and rendering of key machining operations such as sawing and veneering on the 3-D reconstructions of the logs. From the 3-D reconstruction of the log and knowledge of its internal defects, the system can formulate sawing strategies to optimize the yield and grade of the resulting lumber. The system is intended as a decision aid for lumber production planning and an interactive training tool for novice sawyers and machinists.

1 Introduction

Internal features of hardwood logs such as knots, cracks, decay and other anomalies of tree growth determine their ultimate value. If these defects were known prior to the sawing of the log, optimized sawing plans could be devised to achieve greater value from the log. However, since each step in the sawing process is irreversible, the loss in the value and yield is irrevocable. Hardwood lumber production has traditionally had a low conversion efficiency (about 35%) resulting in high wastage and poor utilization of valuable and rapidly diminishing forest resources. Existing technologies to increase lumber value and yield by external log inspection have reached the point that little further progress is expected. It seems reasonable to assume that future gains in lumber value and yield will be possible only by internal log scanning and using the knowledge of the internal log defects during the sawing process to optimize lumber yield and value. Studies of computer axial tomography (CAT or CT) and nuclear magnetic resonance (NMR) scanning for internal log defects [4, 6, 7, 9, 10] have demonstrated that both CT and NMR scanners available today can be used successfully to image the internal features of logs.

In this paper we describe the design and implementation of a **C**omputer **V**ision-based **L**umber **P**roduction **P**lanning **S**ystem (CVLPPS). CVLPPS is based on an earlier system for the detection and 3-D rendering of internal defects of hardwood logs [2]. CVLPPS is currently capable of reconstruction and rendering of the 3-D log model along with its internal defects, simulation and rendering of various machining operations such as veneering and sawing, and suggesting sawing strategies for optimizing lumber value and yield. CVLPPS could be used as a decision support system for lumber production planning as well as an interactive training tool for novice sawyers and machinists enabling them to practice various lumber production strategies on *virtual* logs before working on real logs.

2 Overview of CVLPPS

The current version CVLPPS has five subsystems distinguished by function: (1) Preprocessing and segmentation of individual 2-D CT image slices, (2) Detection and classification of internal defects in the individual 2-D CT image slices, (3) 3-D reconstruction of the internal defects and the internal structure of the log, (4) Simulation of machining operations on the 3-D reconstruction of the log, and (5) Determination of a sawing strategy to optimize lumber value and yield from the 3-D reconstruction of the log. Since, stages (1) and (2) have been described in [2] in reasonable detail, we present only a brief synopsis of their design and functionality for the sake of completeness. Stages (3), (4) and (5) on the other hand, are presented in greater detail.

Stages (1) and (2) in CVLPPS initially adopt a

Proceedings of the Fourth IEEE Workshop on Applications of Computer Vision (WACV'98)
0-8186-8606-5/98 $17.00 © 1998 IEEE

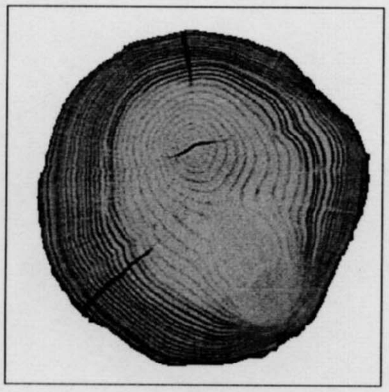


Figure 1: A raw CT image of Red Oak

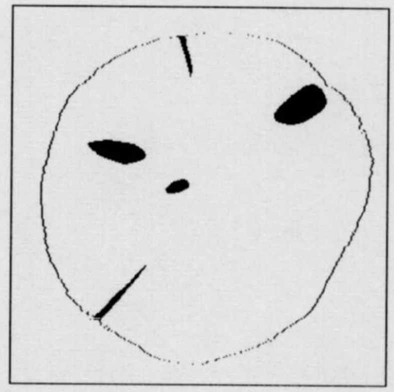


Figure 2: The finally detected 2-D defect-like regions

bottom-up processing approach. The CT images of the logs are captured using a Toshiba TCT 20AX CT scanner with a pixel resolution of 0.75mm by 0.75mm (Fig. 1). Three representative hardwood species that account for over 80% of the US hardwood lumber production were considered: Red Oak, Black Walnut and Hard Maple. The histogram of each CT image slice is computed and subject to selective non-linear smoothing and multiple thresholding [2]. The resulting pixels are classified as either cracks, knots or other. Pixels in the crack class and the knot class are grouped using a region growing algorithm.

The pith (i.e., geometric center) of the log cross-section is computed using the Canny edge operator [3] and the Hough transform for circle detection [1]. Regions obtained from the region growing process are filtered using a minimum area criterion. For a region passing the area test, the orientations of its major and minor axes are computed. Knots and cracks are generally characterized by a major axis passing approximately through the pith (unlike the regions comprising the annual ring structure of the wood), and are easily detected by an orientation test. Morphological features such as the maximum and minimum moments of inertia are used to verify whether the region contains a defect or is defect-free. The contour of the region is then simply represented by the convex hull (for a knot) or a polygon (for a crack). Fig. 2 shows the finally detected 2-D defect-like regions with holes and gaps filled.

3 3-D analysis of defect-like regions

Since the objective of CVLPPS is to detect 3-D log defects, 3-D defects are reconstructed from the 2-D defect-like regions for purpose of verification. 2-D defect-like regions without 3-D support (i.e., with no corresponding defect-like regions in neighboring CT images) are discarded. 2-D defect-like regions with 3-D support from neighboring CT images, are discarded if they do not satisfy the 3-D parameters of a valid defect. In CVLPPS, most ambiguities in the segmentation of 2-D CT images are resolved by a 3-D analysis of defect-like regions across successive CT image slices.

For efficient 3-D analysis, preliminary groups of 2-D defect-like regions are generated from successive CT images using an iterative clustering procedure with the two geometric parameters α and r depicted in Fig. 3. The parameter r denotes the distance of the centroid of the 2-D defect-like region from the pith whereas α denotes the orientation of the 2-D defect-like region with respect to the horizontal axis. Each group is a series of defect-like regions that are spatially connected across CT image slices. A group is classified as a defect if it passes the 3-D test.

Since a knot is a branch that is embedded in the trunk of a tree, the branch angle (i.e., the angle between the branch pith axis and the tree trunk pith axis) often around 45^o. Thus, the angle between the log pith axis and the line passing through the centers of the 2-D defect-like regions in successive CT image slices, is the most important factor in distinguishing a knot from other bright objects, such as a water pocket (Fig. 4(a) and Fig. 4(b)). Other 3-D measurements for knots include the change in region area across successive CT image slices, and the region shape. For a normal knot, the area should change from small to large to small along successive CT slices containing the knot, and the region shape is elliptical for most knots.

For cracks and water pockets, a 3-D orientation measurement and the measurement of the angle between the log pith axis and the line passing through the region centers in successive CT image slices are used to verify whether the group is a valid crack or not. The 3-D orientation test for a typical crack shows that

Proceedings of the Fourth IEEE Workshop on Applications of Computer Vision (WACV'98)
0-8186-8606-5/98 $17.00 © 1998 IEEE

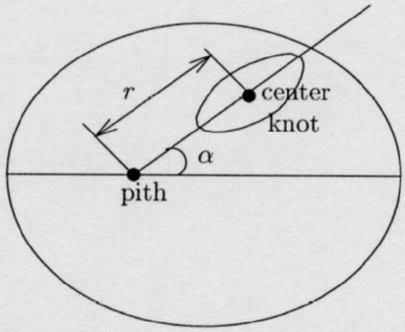


Figure 3: The two geometric values used to group the defect-like regions

the plane containing the major axes of the 2-D crack-like regions in successive CT slices intersects the log pith axis. In a water pocket the line passing through the region centers in successive CT image slices, is roughly parallel to the log pith axis (Fig. 4 (c)).

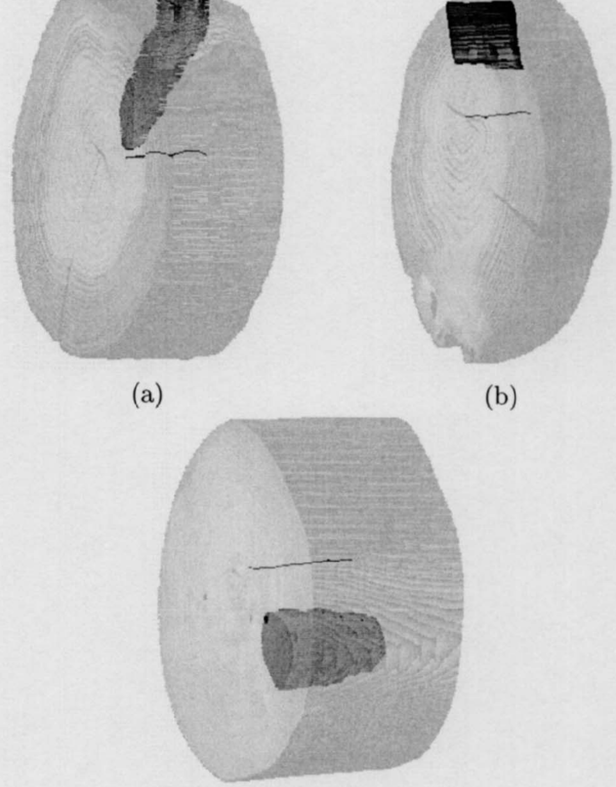
4 3-D visualization and simulation of machining operations

CVLPPS is capable of 3-D reconstruction and visualization of the scanned logs. CVLPPS reconstructs the scanned log in 3-D from the individual 2-D CT image slices and permits viewing of the external features of the log as well as the 3-D defects within the log. The user can manipulate the log via translation and rotation and zoom in/out on the rendered image.

CVLPPS is also capable of simulating machining operations on logs. Currently, CVLPPS simulates the sawing and veneering operations on the 3-D reconstructions of the scanned logs. For the sawing operation, the user can specify the position and orientation of the sawing plane with respect to the log. Once the log is sawed, the user can view the cross-section which contains both, the markings from the growth ring structure as well as the log defects. Simulation of the sawing operation enables the user to view the 2-D boards that would possibly result from subjecting the log to a certain sawing scheme (Fig. 5).

CVLPPS is capable of simulating the veneering operation on the 3-D log reconstruction as well as on 2-D boards that result from the sawing operation. In the former case, the rotary-peeled veneering technique is used where the wood is shaved off the cylindrical surface of the log using a rotary lathe machine. In the latter case, the wood is shaved off the board surface using a slicing machine.

In the simulation of veneering operations, the user can specify the orientation and length of the log or board and the thickness of the veneer. The veneer-



(a) (b) (c)

Figure 4: (a) A detected 3-D knot with branch angle of 46^o (b) A detected 3-D crack (c) A detected 3-D water pocket

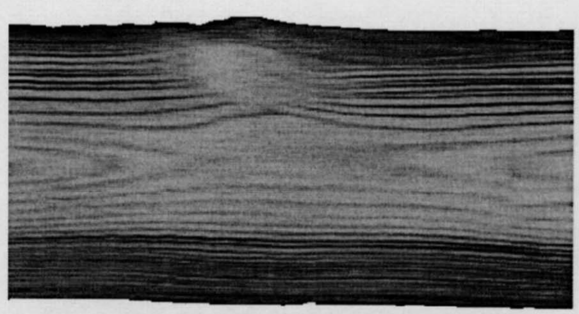


Figure 5: Result of a simulated sawing operation

Figure 6: Veneer image generated from a simulated rotary-peeling veneering operation

ing operation is essentially one of mapping the points on the veneer surface onto the veneer image plane. The veneering operation is made efficient by mapping the shaving plane or peeling cylinder on each individual CT image slice. The shaving plane maps onto a line (with thickness that equals the veneer thickness) whereas the peeling cylinder maps onto a circle (with thickness that equals the veneer thickness) on each CT image slice. The intersecting pixels of each CT image slice with the line or circle are backprojected into the veneer coordinate reference frame and from there mapped onto the veneer image plane. An interpolation process is used to reconstruct a smooth realistic veneer image from the mapped CT image pixels (Fig. 6).

5 Optimal sawing strategy selection

Once the 3-D log information (i.e., the 3-D geometry of the log and its internal defects) is obtained via image analysis, the next problem that needs to be tackled is that of optimal sawing strategy selection. The 3-D log information should be used to determine a sawing strategy for the log that would maximize the value and yield of the resulting lumber given certain lumber size constraints. In this paper we present a solution for optimal sawing strategy selection under the assumption that the *live sawing method* is used to cut the log. Sawing methods in the lumber manufacturing industry are defined based on two factors: (i) the relationship of the sawing planes with each other and (ii) the number and magnitudes of angular rotations of the log permitted during the sawing process. The live sawing method (Fig. 7) in which the sawing planes are parallel to each other and angular rotations of the log are restricted to 0^o (no rotation) or 180^o (complete flip) is the most popular sawing method for hardwood sawmilling.

5.1 Lumber value determination

In practice, the value of a piece of lumber is determined by it's species group, it's grade, it's size (width, thickness and length) and by market demand. Hardwood lumber grades are a function of the number, type and size of defects appearing on the lumber surfaces

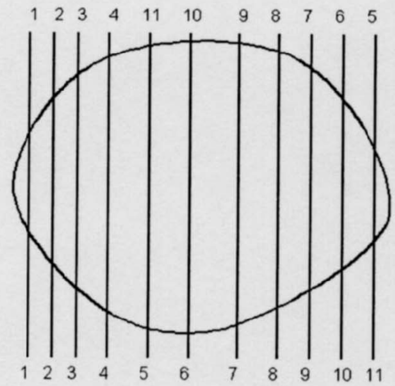


Figure 7: Live sawing with parallel planes. Sawing without log rotation is indicated by numbers at the bottom and sawing with log rotated by 180^o after cut #4 is indicated by sawing plane numbers at the top.

and are determined according to the NHLA rules [8]. Thus the value v of a piece of lumber, is obtained using the following formula:

$$v = VP_sP_gP_wP_tP_l \quad (1)$$

where V is the lumber volume, P_s is the base price for unit volume of a certain species group lumber, P_g is the price factor related to a certain lumber grade, and P_w, P_t, and P_l are price factors related to lumber width, lumber thickness and lumber length, respectively. Note that the effect of market demand can always be represented by incorporating an additional multiplicative factor in eq. (1).

5.2 Formulation of the problem

The optimal sawing strategy selection problem is formulated in the context of the live sawing method (Fig. 7). For simplification, the log is modeled as a right cylinder with a possibly tapering cross-section. Lumber derived from the larger cross-section, which is shorter than the total log length, is not considered in the optimization process. Some variables used in the section are defined below: $T = \{T_1, T_2, \ldots, T_t\}$ is a finite set of lumber thickness in mm, t_{min} is the minimum of the elements in T, $W = \{W_1, W_2, \ldots, W_w\}$ is a finite set of lumber widths in mm, w_{min} is the minimum of the elements in W, c is the sawing plane step or resolution in mm, K is a constant which denotes the kerf of the sawing planes in mm (the kerf is a tolerance factor that takes into account the physical width of the saw and the deviation of the saw from the vertical cutting plane), CR is the cutting range in mm, and $N = \lfloor CR/c \rfloor$ is the total number of cutting planes within the cutting range. We assume that the

Proceedings of the Fourth IEEE Workshop on Applications of Computer Vision (WACV'98)
0-8186-8606-5/98 $17.00 © 1998 IEEE

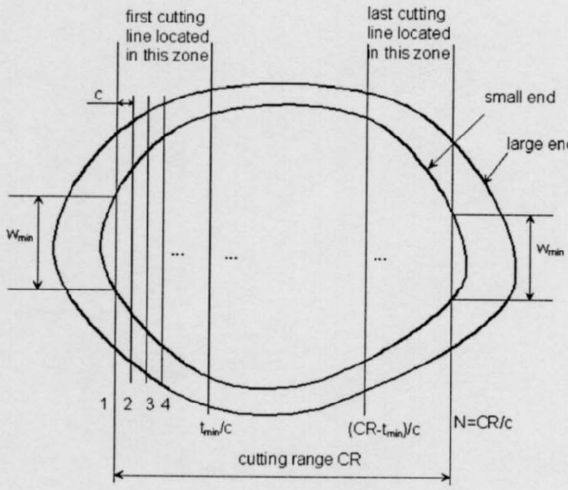


Figure 8: Cutting range determination

lumber thickness values $T_1, T_2, \ldots, T_t$ (in mm) and c (in mm) are integers. In most practical cases $|T| \leq 10$.

5.2.1 Cutting range determination

Each log has a cutting range in which a cut generates a valid lumber piece with the same length as the log and width $\geq w_{min}$. Since the boundary of the small end of the log is known, it is trivial to obtain the cutting range CR for a fixed saw orientation using a simple scanning operation. Any two sawing planes within this range will produce a valid lumber piece with a specified thickness. To simplify the computation, it is assumed that the possible sawing plane locations are discretized in steps of c mm (Fig. 8). The value of c is an integer and a realistic value for c is 1 mm. Then $N = \lfloor CR/c \rfloor$ represents the number of possible cutting planes within the cutting range CR. The possible cutting planes are enumerated as $1, 2, \ldots, N$.

From Fig. 8 it is obvious that the first cutting plane must be one of cutting planes between 1 and $\lceil t_{min}/c \rceil$, because the first cutting plane on the left side of cutting plane 1, would produce an invalid lumber piece (thus wasting wood) and one on the right side of cutting plane $\lceil t_{min}/c \rceil$, would cause a lumber piece with thickness of at least t_{min} to be missed. Using the same argument, the last cutting plane must lie between $(N - \lfloor t_{min}/c \rfloor)$ and N.

5.2.2 Mathematical model for optimization

Inputs to the optimization problem include T, W, various lumber price factors, and the log data (which includes the reconstructed 3-D log model). The required output is a cutting pattern (i.e., set of sawing plane locations) which maximizes the yield and value of the resulting lumber. Let $C = \{1, 2, \ldots, N\}$ be a finite set representing the possible cutting planes for the log. Let $S = \{s_0, s_1, \ldots, s_n\}$ be a subset of C satisfying the following constraints: $1 \leq s_0 \leq \lceil t_{min}/c \rceil$; $N - \lfloor t_{min}/c \rfloor \leq s_n \leq N$; and $(s_i - s_{i-1} - \lceil K/c \rceil)c \in T$ where $1 \leq i \leq n$. Thus, S is a feasible cutting pattern for the log (Fig. 9). Suppose the lumber piece cut by cutting planes s_{i-1} and s_i has value v_i. Let $\mathbf{v} = (v_1, v_2, \ldots, v_n)$ be an n-vector of lumber values corresponding to the feasible cutting pattern $S = \{s_0, s_1, \ldots, s_n\}$. For $S \subset C$, we define $v(S) = \sum_{j \in S} v_j$ to be total value yield of cutting pattern S. If $\Phi = \{S_i\}$ is the collection of subsets of C that constitute feasible cutting patterns then the problem is one of constrained combinatorial optimization where we are interested in determining a cutting pattern S^* such that:

$$S^* = \arg(\max_{S \in \Phi} v(S)) \tag{2}$$

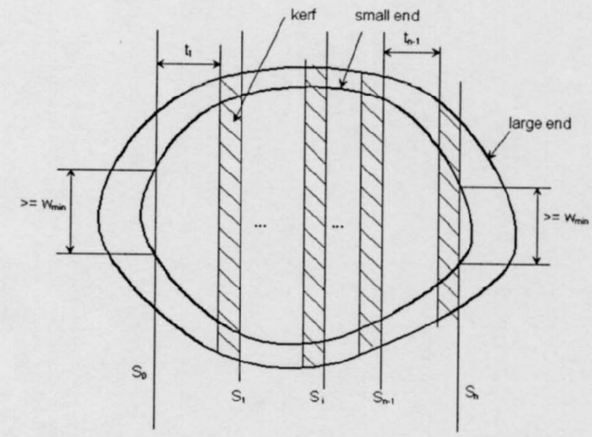


Figure 9: A feasible sawing pattern S

We show that the optimization problem expressed in eq. (2) can be modeled as the *Shortest Paths Problem* in a directed graph [5]. Let each possible cutting plane i be a node i in a directed graph (digraph) G. There exists a directed edge e_{ij} from node i to node j in G (where $j > i$) if cutting the log along planes i and j produces a valid piece of lumber. Note the lumber piece between cutting planes i and j contains the kerf near cutting plane j. The value v_{ij} of the resulting piece of lumber is computed based on the quality of the visible lumber surfaces resulting from the cutting planes i and $(j - \lceil K/c \rceil)$. We select $w_{ij} = -v_{ij}$ to be the weight of the edge e_{ij} in digraph G. The problem therefore is to find a shortest directed path from a node $k \in \{1, \ldots, \lceil t_{min}/c \rceil\}$ to a node $l \in \{(N - \lfloor t_{min}/c \rfloor), \ldots, N\}$.

Proceedings of the Fourth IEEE Workshop on Applications of Computer Vision (WACV'98)
0-8186-8606-5/98 $17.00 © 1998 IEEE

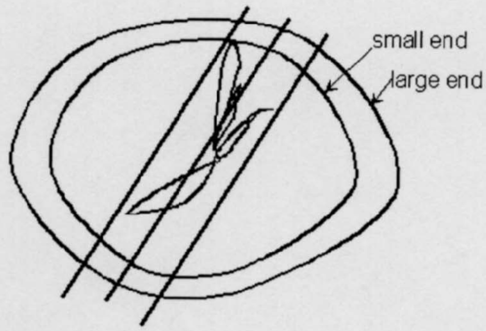


Figure 10: Heuristic selection of the initial saw orientation

5.3 Algorithm for Sawing Strategy Determination

The following algorithm is used for the *Shortest Paths Problem* in order to arrive at an optimal sawing strategy.

(1) *Selection of the initial saw orientation:* If the defect configuration has a major orientation axis in the cross-sectional plane then select the saw orientation parallel to the major orientation axis (Fig. 10). Else determine the saw orientation by an exhaustive search. The total number of possible saw orientations may range from 45 to 180 (corresponding to orientation resolutions from 4^o to 1^o in the range $[0^o, 180^o]$). Perform the following steps for each saw orientation.

(2) Determine the cutting range CR given the boundary of the smaller log cross-section, w_{min} and the selected saw orientation from step 1.

(3) Determine $N = \lfloor CR/c \rfloor$, the total number of possible cutting planes within the cutting range.

(4) Construct the digraph G. For each cutting plane i where $1 \leq i \leq N$ create a node $i \in G$. For each node $i \in \{1, \ldots, \lceil t_{min}/c \rceil\}$ do the following:

(a) For each $t \in T$ let $j = i + \lceil (t + K)/c \rceil$

(b) If $j \leq N$ and directed edge $e_{ij} \notin G$ then add e_{ij} with weight $w_{ij} = -v_{ij}$ to G.

(c) Recursively create all possible directed edges starting from node j in the same way as for node i.

(5) For each node $i \in \{1, \ldots, \lceil t_{min}/c \rceil\}$ find the shortest paths from i to all nodes in G.

(6) Within all node pairs (i, j) where $1 \leq i \leq \lceil t_{min}/c \rceil$ and $(N - \lfloor t_{min}/c \rfloor) \leq j \leq N$ find one node pair (i^*, j^*) with the minimum shortest path value. The shortest path corresponding to the node pair (i^*, j^*) is the solution to the optimal sawing pattern problem (eq. (2)).

6 Conclusions and Future Directions

The current version of CVLPPS is capable of detection and 3-D rendering of defects such as knots and cracks in hardwood logs of select hardwood species. CVLPPS is capable of 3-D reconstruction and rendering of the log along with its internal defects. CVLPPS is also capable of simulating and rendering key machining operations such as sawing and veneering on the 3-D log reconstructions and automatic determination of sawing strategies for optimizing lumber value and yield. The current version of CVLPPS could be used as a decision aid by sawyers and machinists for lumber production planning as well as an interactive tool for training novice sawyers and machinists. In future versions of CVLPPS the lumber grading process would be enhanced to account for more hardwood species and lumber defects in conjunction with aesthetic (subjective) aspects based on wood grain texture.

Acknowledgments

This research was partially funded by a research grant from the US Dept. of Agriculture.

References

[1] D.H. Ballard and C.M. Brown, *Computer Vision*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1982.

[2] S.M. Bhandarkar, T. Faust and M. Tang, A system for detection of internal log defects by computer analysis of axial CT images, *Proc. IEEE WACV'96*, 258-263, 1996.

[3] J. F. Canny, A computational approach to edge detection, *IEEE Trans. PAMI*, 8(6):679-698, 1986.

[4] S.J. Chang, J.R. Olson, and P.C. Wang, NMR imaging of internal features in wood, *For. Prod. Jour.*, 39(6):43-49, 1989.

[5] S. Even, *Graph Algorithms*, Computer Science Press, Potomac, MD, 1979.

[6] S. Guddanti and S.J. Chang, Replicating sawmill sawing with TOPSAW using CT images of a full-length hardwood log, *For. Prod. Jour.*, 48(1):72-75, 1998.

[7] P. Li, A.L. Abbott and D.L. Schmoldt, Automated analysis of CT images for the inspection of hardwood logs, *Proc, IEEE ICNN*, 1744-1749, 1996.

[8] National Hardwood Lumber Association, *Rules for the measurement and inspection of hardwood and cypress lumber*, NHLA, Memphis, TN, 1982.

[9] L.G. Occena and D.L. Schmoldt, GRASP: A prototype interactive graphic sawing program, *Forest Prod. Jour.* 46(11/12):40-42, 1996.

[10] D.L. Schmoldt, J. He and A.L. Abbott, A comparison of several artificial neural network classifiers for CT images of hardwood logs, *Proc. SPIE Conf. Mach. Vis. Appl. Ind. Inspec. VI.* 3306:34-43, 1998.