Knot detection in computed tomography images of partially dried jack pine (*Pinus banksiana* Lamb.) and white spruce (*Picea glauca* (Moench) Voss) logs from a Nelder type plantation

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Abstract

X-ray computed tomography (CT) of logs means possibilities for optimizing breakdown in sawmills. This depends on accurate detection of knots to assess internal quality. However, as logs are stored they dry to some extent, and this drying affects the density variation in the log, and therefore the X-ray images. For this reason it is hypothetically difficult to detect log features in partially dried logs using X-ray CT. This paper investigates the effect of improper heartwood-sapwood border detection, possibly due to partial drying, on knot detection in jack pine (*Pinus banksiana* Lamb.) and white spruce (*Picea glauca* (Moench) Voss) logs from New Brunswick, Canada. An automatic knot detection algorithm was compared to manual reference knot measurements, and the results showed that knot detection was affected by detected heartwood shape. It was also shown that logs can be sorted into two groups based on how well the heartwood-sapwood border is detected, to separate logs with a high knot detection rate from those with a low detection rate. In that way, a decision can be made whether or not to trust the knot models obtained from CT scanning. This can potentially aid both sawmills and researchers working with log models based on CT.

Key words: CT scanning, jack pine, knot detection, white spruce

19 Introduction

20 As industrial X-ray computed tomography (CT) scanners were introduced to the market a few
21 years ago (Guidiceandrea 2011), new opportunities for optimizing production in sawmills
22 have arisen. Since CT scanning uses X-rays, internal log features with density variation can
23 be distinguished. Examples of such features are heartwood-sapwood (Longuetaud et al. 2007),
24 knots (Bhandarkar et al. 1999, Andreu and Rinnhofer 2003, Longuetaud et al. 2012,
25 Johansson et al. 2013), checks (Bhandarkar et al. 1999, Andreu and Rinnhofer 2003,
26 Wehrhausen et al. 2012), decay (Schmoldt et al. 1996) and resin pockets (Oja and Temnerud
27 1999). Recent studies on automatic knot detection in CT images of logs include Krähenbühl et
28 al. (2014) and Roussel et al. (2014), who developed two algorithms that are promising in
29 terms of detecting knots in sapwood.

30 Once these log features are detected, sawmill production can be controlled in various ways to
31 make sure that the value of the resulting sawn timber is maximized with regard to these
32 internal features. For instance, Rinnhofer et al. (2003) tested a semi-automatic optimization
33 method using CT scanning of spruce and larch logs, indicating a possible yield increase of 6 –
34 9 % for spruce, but zero for larch. Lundahl and Grönlund (2010) varied rotation, offset and
35 skew of Scots pine (*Pinus sylvestris* L.) log models derived from CT scanning, choosing the
36 optimal position for volume yield. This increased volume yield by 4.5 % compared to sawing
37 logs horns down and centered. In Berglund et al. (2013), it is shown that choosing an optimal
38 rotational position of a Scots pine and Norway spruce (*Picea abies* (L.) Karst.) logs based on
39 CT data can improve value yield by about 13 %. Stängle et al. (2015) showed that value and
40 volume yield of beech (*Fagus sylvatica* L.) logs can be increased by up to 24 % when
41 optimizing log rotation based on CT data, compared to an average value from 12 different
42 rotations.

However, some peculiarities of the sawmill industry make scanning and detection of density related features in logs difficult. For instance, the moisture content of the log will affect scanning results since wood that contains water have a higher density than wood which is dry (Lindgren 1991). Logs that are stored for a long time, *e.g.* in a log yard, can dry to a varying extent depending on the bark retention/damage on the log and the surrounding environment (Droessler et al. 1986, Defo and Brunette 2006). Since the exact moisture distribution in a log is usually unknown prior to scanning, detection algorithms need to be prepared to handle variations in moisture content within logs.

In particular, the knot detection algorithm described by Johansson et al. (2013) depends on an accurate detection of pith, sapwood-heartwood border and outer shape of the log. In a fully dried log, the sapwood density will be very close to that of the heartwood, thus making distinction between the two nearly impossible. If a log is partially dried, the sapwood-heartwood border will be possible to discern in some places but not in others, since “dry pockets” are formed that makes separation between heartwood and sapwood difficult in certain regions of the log. Another complication is large knots, which can have an adverse effect on the detection of sapwood-heartwood border despite measures taken within the detection algorithm to avoid it. The detection algorithm is further detailed in Baumgartner et al. (2010). One example of a poorly detected sapwood-heartwood border is shown in Figure 1. An irregular heartwood shape might lead to irregularly shaped detected knots if the Johansson et al. (2013) algorithm is used.

Furthermore, when these problems arise, there is usually no way for the sawmill to know whether or not logs have drying problems. This could be solved by using the data from CT scans of the logs, since this data contain information on log density and therefore, to some extent, moisture content in different regions of the logs.

Given the hypothetical difficulties of detecting knots properly in partially dried out logs or with large knots, the objective of this study was to apply the knot detection algorithm developed by Johansson et al. (2013) on partially dried logs of jack pine (*Pinus banksiana* Lamb.) and white spruce (*Picea glauca* (Moench) Voss), to evaluate how the drying affects the detection results. A secondary objective was to classify the logs with high and low knot detection rates, respectively, in a way that can be measured by CT scanning. In this way, when scanning partially dried logs for knots, it can be known a priori what the chances are that the knot detection will be successful. This classification was based on the shape regularity of the detected sapwood-heartwood border, which hypothetically will be affected both by dry pockets and large knots.

Materials and Methods

Tree Selection

Trees were harvested from a Nelder Spacing Experiment type 1a design (Nelder 1962) established in 1977 near Woodstock, New Brunswick, Canada (46.16° N, 67.58° W). The circular plot was divided into two sections, where one was dedicated to jack pine and the other to white spruce. Stand densities varied from about 600 stems/ha on the periphery of the plot to 12 000 stems/ha in its centre. No silvicultural treatments (e.g. thinning) were performed after plantation establishment.

A total of 53 trees were selected for this study, 22 jack pine and 31 white spruce. These were 32 years old at the time of harvest in December 2009. During harvesting, dead trees or trees with defects such as forks were removed from the sample. After felling, stems were topped at a 7 cm diameter to consider only merchantable volume and transported to Quebec where they were stored outdoors for about 5 months. Stems were thereafter bucked into 2.5 m-long logs in May 2010. Overall, 173 logs were produced in this way and sent to Institut national de la

recherche scientifique (INRS) in Quebec City for CT scanning, which was performed in June-July 2010. The logs were stored outdoors between operations.

X-ray scanning and data preparation

X-ray CT images were obtained for all stems. Scans were performed every millimeter along the logs with a Siemens Somatom Sensation CT scanner. The physical pixel size for each cross-section was 0.605 mm/pixel. The pixel resolution was 512×512.

Forty of these logs were selected for this study, 20 of each species. The selection was made to maximize the range of tree and log characteristics, such as diameter at breast height (DBH), maximum branch diameter, height of the green crown and log type (butt-, middle- and top logs). These features are summarized in Table 1. Thirteen butt logs, fourteen middle logs and thirteen top logs were chosen. These were taken from 13 jack pine trees and 14 white spruce trees, so in some cases several logs came from the same tree.

Knot detection algorithm

A knot detection algorithm developed by Johansson et al. (2013) was applied to the CT stacks of all logs of this study. Prerequisites for the algorithm are a detected pith position, an outer shape border and a sapwood-heartwood border. Pith detection was done by using Hough transforms as described by Longuetaud et al. (2004). Sapwood-heartwood and outer shape border were found using a series of filters applied on polar images of the logs' CT images, where the polar images had their origin at the pith. This was basically the algorithm described by Longuetaud et al. (2007), with the modifications described by Baumgartner et al. (2010). Both borders were described by polar coordinates for each CT cross-section, with 360 points for each slice, *i.e.* one radius at every angular degree.

In short, the algorithm works by creating concentric surfaces (CS's) that extend outwards from the pith of the log. CS's are close to cylindrical shells cut out at a certain radius in the

CT stacks, following either the heartwood shape or the outer shape of the log. Ten CS's are used for each log, of which at least five need to be from the heartwood since knots are more easily found in the heartwood (Pietikäinen 1996, Tong et al. 2013). In all heartwood CS's, knot objects are found using a thresholding operation, after which ellipses are fit to the objects if these are of a reasonable size and orientation. The knot ellipses are then matched together to form knots. The knots in the heartwood are then extrapolated to trace knots in the sapwood, by finding regions of interest in the sapwood CS's and using morphological dilation to find the position and size of the knot within that region. After this, the knot end positions are calculated, and the dead knot border is set to the point where the knot reaches its maximum diameter. Finally, a parameterized knot model is created using regression models for the size and position of each knot.

The parameters used in the algorithm were originally set to achieve a high detection rate and low amount of false detections in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst) logs. In this study, we used the same parameters as in the Johansson et al. (2013) study, where further details can be found. For instance, we used 10 CS's in total, the size of the median filter used in each CS was 510×510 mm, and so on.

Reference measurements of knots

Reference measurements were made manually in the CT images to enable validation of knot geometry including size, position and end point. The measurements were done by drawing ellipses around knots in log CS's in the same manner as in Johansson et al. (2013). Ellipses for each non-occluded knot were drawn at radii at 10%, 20%, ..., 90% of the log radius. This yielded a total of nine ellipses per knot from the pith to the outer surface of the log. For occluded knots, ellipses were drawn to the knot end point, the position of which was marked in order to validate detection of the knot end. For the jack pine logs, 778 knots were measured, while 955 knots were measured for white spruce. Not all knots were measured, but

140 at least half of the knot population in each log was included. The number of knots per log
141 depended on the knottiness of the log but varied between 26 and 131. The knots were chosen
142 in a way that varied size, position and type as much as possible. Since the manual
143 measurements were made in CT images and not on actual wood surfaces, there is a
144 measurement error present. This error is even higher in the sapwood region, since the contrast
145 between knot and regular wood density is lower than in the heartwood. The manually drawn
146 ellipses were parameterized using the same model as the automatically measured knots for
147 comparison.

148

Classification of log heartwood shape

For all logs, the detected sapwood thickness was calculated by subtracting the heartwood-sapwood border radius from the outer shape radius, expressed in millimeters. In each CT cross-section, the standard deviation of sapwood thickness was then calculated as a measure of dispersion. A high standard deviation indicates an irregularly shaped detected heartwood. This was verified by visual inspection of the CT stacks, to make sure that most of the variation in heartwood shape was due to dry pockets, and not ovality etc. Finally, to get a measure that could be used for the entire log, the average standard deviation over all cross-sections in the log was calculated. This was done for all logs of the study.

Logs were grouped in two categories based on this measurement. The cut-off was chosen with the aim of sorting them into groups of approximately the same size, one group with a lower standard deviation and one group with higher. The group with the lower standard deviation was named the Regular Heartwood (RH) group, while the other group was named the Irregular Heartwood (IH) group. The cut-off was done at a sapwood thickness standard deviation of 6 mm. Twenty-one logs were below this threshold and were assigned to the RH group, while 19 were above and were thus assigned to the IH group.

Results

In Figure 2 the knot detection rate depending on the standard deviation of the detected sapwood thickness is presented.

Figure 2, shows a decreased knot detection rate with an increased standard deviation, but not with any large significance. The coefficient of determination (R^2) value is rather low, 0.19. For the linear regression model, the p-values for the intercept and the slope were 2.4×10^{-10} and 0.0044, respectively, indicating that the model terms are significant at the 99% level, despite the low R^2 . However, this is not enough to draw any definite conclusions, especially

given the small sample used. Using $p = 0.01$ as a test for significance is not necessarily enough according to Colquhoun (2014). The decrease in detection rate should thus be considered very carefully.

The knot detection rates and rate of false detections are presented in Table 2, for the RH and IH groups and also separated by species. Overall, 937 knots were detected in the RH group and 796 in the IH group.

A two-proportion z-test was done, with p_1 = detection rate of the RH group, and p_2 = detection rate of the IH group. Choosing a z-test was justified by the large sample size of both groups. Using the null hypothesis that $p_1 = p_2$ gives a z of 10.2 ($n_1 = 955$, $n_2 = 778$) which means the null hypothesis can be rejected at the 99.9% level, *i.e.* the two detection rates are probably not similar.

Most of the false positives that were found, were knots that were detected as two knots. These knots usually had a low density centre, which split the knot in two high density regions as shown in Figure 3.

The detection accuracy of knot diameter, position and end point is presented in Table 3. Here, the logs are not separated by species, only based on their RH and IH groups. A negative mean error means that the algorithm underestimates the knot feature. Diameter validation was done for three different size classes: small (<10 mm), medium (10–20 mm) and big knots (>20 mm).

Discussion

For almost all features presented in Table 3, the group with more regular heartwood (RH) outperformed the other (IH) group. In comparison to the results presented by Johansson et al. (2013) for Scots pine and Norway spruce, the results presented here are similar, especially for the RH group of logs, with an RMSE for knot diameter of around 5 mm. These results

confirm that partially dried logs could induce knot detection problems for the Johansson et al. (2013) algorithm if they are characterized by an irregular heartwood area. The knot detection algorithm works with concentric surfaces based on the sapwood-heartwood border, and a poorly detected border results in distortions of the knot shape throughout the concentric surfaces that means knots are not recognized. This could be the effect both of partial drying and possibly large knot clusters, but the underlying factors are less relevant since we used the detected heartwood shape as an indicator.

The knot detection is in some cases easier in dried sapwood (Johansson et al. 2013), so full drying of logs is a smaller problem than partial drying, since the latter results in distortion effects of knots. If a log is fully dried, the algorithm assumes that the heartwood goes all the way out to the surface of the log, but knot shapes are retained and the contrast between knots and clear wood is high.

For the knot height and knot end position, the results for the RH group is somewhat better than in Johansson et al. (2013), while the IH group performance is similar to Johansson et al. (2013). The overall improvement could be due to the higher longitudinal resolution in our data, compared to Johansson et al. (2013), 1 mm per slice compared to 10 mm per slice. The rotational position accuracy is a bit worse in this study than in Johansson et al. (2013), for both log groups, but this could be related to the fact that the logs from this study were partially dried. Nonetheless, detection of all these features was somewhat similar to those reported by Johansson et al. (2013), which demonstrates that the knot detection algorithm method developed for Scots pine and Norway spruce could be adapted for other wood species such as jack pine and white spruce.

The plots in Figure 4 show the detection of knot diameter and knot end in more detail. There was a large group of knots where the distance from pith to knot end was underestimated, *i.e.* the detection algorithm estimated the knot to be occluded while in reality it continued all the

way out to the surface of the log. In this material, very few occluded knots were observed since the trees were only 32 years old at the time of harvest. As discussed in Johansson et al. (2013), this error is due to the low contrast between knots and sapwood.

The difference between the two species, with a larger detection rate for jack pine compared to white spruce, could have several explanations that were not investigated in detail. Knots in pine trees are usually larger but less numerous than in spruce trees, facilitating better detection. The average diameter of the largest branch in each tree, for the jack pine and white spruce trees used in this study, were 33.9 and 30.5 mm, respectively. Also, Duchateau et al. (2013) found larger knot sizes in jack pine than in black spruce (*Picea Mariana* Mill.). Even though the spruce species was different in their study, it indicates a difference in knot size between pine and spruce that could be a reason for different detection rates. Furthermore, Bucur (2003) has reported that knot density is twice the average density of the surrounding wood when scanning a southern pine board. In Scots pine and Norway spruce, Boutelje (1966) has reported that wood density of knots was respectively 0.925 g/cm³ and 1.01 g/cm³ on average, while that of wood around knots was similar for both species (~0.66 g/cm³). Even though these wood species differ from those of this study, it can be hypothesized that size and quantity of knots could have a larger impact on detection rate than knot density in partially dried logs. Another factor could be the size of logs, since larger logs mean larger regions in which to search for knots. The average DBH for the jack pine trees of this study was 17.2 cm, whereas the average DBH for the white spruce trees was 17.0 cm. Also, the average volume of all the harvested jack pine trees was 238.7 dm³, while the average volume of the white spruce trees was 175.4 dm³ (Belley 2014).

The results indicate that it could be beneficial to measure and classify the detection of the sapwood-heartwood border in logs when using CT scanners in sawmills. Furthermore, they show that a proper management of the log yard with respect to moisture content is important

for obtaining good scanning results. Logs that are partially dried out and therefore might fall in the IH group of this study, need to be handled with this in mind. Since the optimization results based on CT knot detection cannot be fully trusted, sawing of these logs could be optimized using only their outer shape, ignoring internal quality. When scanning logs for research purposes, the same is true as for the sawmills. If possible, only logs with a regular heartwood shape should be used in databases of knots from CT scanned logs, if the results of the studied knot detection algorithm were used. This does not mean that the CT data from the irregular heartwood group should be discarded, just that the results from the Johansson et al. knot detection algorithm can be kept or discarded based on heartwood irregularity.

It should be noted however that the logs in this study were rather small given their relatively young age, therefore making knot detection more difficult. For larger logs, the problems with dried out areas of the sapwood might be smaller.

It can be concluded that knot detection using the algorithm developed by Johansson et al. (2013), performs worse in logs of jack pine and white spruce when the sapwood-heartwood border is irregular or detected poorly. It is however possible to group logs based on irregularity of the heartwood shape, in order to obtain one group with a relatively high detection rate.

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Table 1. Range of tree features for the trees from which the chosen logs were taken in this study.

	DBH ^a (cm)	Maximum branch diameter (mm)	Green crown height (m)
Average	17	26	2.9
Minimum	10	13	0.8
Maximum	26	40	5.8

^aDiameter at breast height

Table 2. Knot detection rates and amount of false positives, for all logs and separated by species and heartwood shape regularity as measured by the standard deviation of the sapwood thickness. Also, the results for all logs regardless of grouping is presented.

	Jack pine		White spruce		All		
	Detection rate	False positives	Detection rate	False positives	Detection rate	False positives	Number of detected knots
RH group	87.3%	1.9%	71.2%	4.9%	79.0%	3.5%	937
IH group	69.0%	4.5%	47.2%	7.5%	56.0%	5.0%	796
Both groups	79.6%	2.9%	59.3%	6.0%	68.4%	4.7%	1733

Table 3. Detection accuracy of knot diameter, position and end point for all logs.

Heartwood shape group	Knot feature	Mean error	SD ^a	RMSE ^b	R ^{2,c}	Sample size
RH	Dia (0,10) (mm)	-0.178	2.68	2.68	0.24	2807
RH	Dia [10,20) (mm)	-3.44	5.03	6.09	0.072	2221
RH	Dia [20,∞) (mm)	-6.49	10.6	12.4	0.00	266
RH	Dia total (mm)	-1.87	4.87	5.21	0.36	5294
RH	Height position (mm)	-1.16	7.03	7.13	-	5258
RH	Rotational position (°)	-0.206	5.06	5.07	-	5258
RH	Knot end ^d (mm)	-6.62	18.1	19.3	0.15	937
IH	Dia (0,10) (mm)	-0.483	2.73	2.78	0.16	1511
IH	Dia [10,20) (mm)	-5.26	5.68	7.74	0.014	1203
IH	Dia [20,∞) (mm)	-10.3	10.4	14.6	0.0024	302
IH	Dia total (mm)	-3.37	6.15	7.01	0.21	3016
IH	Height position (mm)	-2.81	9.74	10.1	-	3011
IH	Rotational position (°)	0.0199	6.25	6.25	-	3011
IH	Knot end (mm)	-11.7	24.3	26.90	0.10	796

^astandard deviation of detection error

^bRoot Mean Square Error

^ccoefficient of determination

^dradial distance from pith to knot end, *i.e.* a straight line

Note: Data is sorted by heartwood shape group (RH or IH) and knot diameter class (small, medium, and big).

Figures

Figure 1

Figure 2

Figure 3

Figure 4

Figure captions

Figure 1. Cross section of CT scanned jack pine log, with parts of the sapwood dried out (*i.e.* low density dark zones in the outer rings), and parts still having high moisture content (*i.e.* high density white zones in the outer rings). The dashed bright line shows the heartwood-sapwood border detected by the Baumgartner et al. (2010) algorithm. If the dry pocket borders the heartwood-sapwood border, it is difficult to tell the difference between the two types of wood since they have almost the same density. Also, the detection result is affected by the presence of large knots.

Figure 2. Knot detection rate plotted against standard deviation of sapwood thickness, for all logs of the study. A linear regression line fitted to the data is included as well, with a coefficient of determination (R^2) of 0.19. The vertical dashed line indicates where the cut-off was made between regular and irregular heartwood groups.

Figure 3. An example of a “false positive” that is in fact a knot that has been detected as two, due to the low density region in the center of the knot. Figure 3a shows the knot viewed in a CT cross-section, while Figure 3b shows the same knot in a concentric surface, as an ellipsoid shape. The bright marks, indicated by arrows, show two knots according to the detection algorithm. The wood species is white spruce.

Figure 4. Scatter plots for the RH and IH groups showing automatic and manual measurements of knot size and knot end point. Measurements from jack pine are represented by points, measurements from white spruce by plus signs. An identity line is included as reference. 4a: RH group, average knot diameter. Each point represents the average of all diameter measurements from one knot. 4b: IH group, average knot diameter. Each point represents the average of all diameter measurements from one knot. 4c: RH group, knot end. Each point represents one knot. 4d: IH group, knot end. Each point represents one knot. The values in 4c and 4d were calculated as the shortest radial distance from the pith to the knot end.