X-ray inspection for boreholes in intact trees

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1 Introduction

In December 2009, exit holes and the larvae of the Citrus long-horned beetles (*Anoplophora chinensis*) were discovered in Boskoop, The Netherlands. This beetle is listed as a quarantine organism (Council directive 2000/29/EC). As a result, the Plant Protection Service of the Netherlands (PD) immediately took measures: all deciduous trees within a range of 100 m were removed and destroyed. Furthermore, European legislation requires that a buffer zone with a range of 2 km had to be applied.

The Citrus long-horned beetle is native to China and other nearby Pacific Rim countries (Moraal & Wessels-Berk, 2007). They were probably introduced in The Netherlands through import of wood material from one of these countries (Moraal & Wessels-Berk, 2007). After import, wood material originating from infested areas should be monitored for the presence of any life stage of the long-horned beetle including egg, larva and pupa. Early detection would allow implementation of measures to reduce the incidence of beetle introduction. Besides the presence of life stages of the Citrus long-horned beetle, other symptoms may indicate long-horned beetle infestation. One such symptom is the presence of boreholes.

X-ray provides an important contribution to current research related to early and non-invasive detection of boreholes. Work on this line was carried out by Fischer & Tasker (1945), Cruvinel *et al.* (2003) and Tomazelllo *et al.* (2008) who all used X-ray photographs to inspect wood pieces for the presence of insect infestation. In 2009, preliminary tests were done to study whether X-ray indeed allows the detection of boreholes. Results demonstrated that artificial holes and long-horned beetle induced boreholes were detectable in wood pieces of about 20 × 100 mm (de Kogel *et al.*, 2010). For detection of boreholes in intact trees, the X-ray system was not large enough.

X-ray systems are commonly used for luggage inspection. The size of these systems is sufficient for inspection of intact trees. The first objective of this study is to determine whether such an X-ray system is able to visualise boreholes in intact trees. The present study is partly based on human inspection of X-ray images to determine whether boreholes are visible or not. But, human inspection requires skilled personal which in-turn lead to high costs. Today, machine vision is often used to detect irregularities in images. The second objective of this study is to determine the ability of machine vision to detect boreholes in intact trees. A clear visualisation of boreholes by means of X-ray may depend on many factors. Factors as tree position, the stem diameter, the borehole diameter and position, the presence of boredust and the humidity of the wood are expected to be of prime importance. The third objective of this study is to determine the effect of the above mention factors on the visibility of boreholes in intact trees.

2 Materials and methods

2.1 X-rayed objects

Wooden axles, stems and intact trees were subjected to X-ray to visualise artificial and real boreholes. Because the humidity of the wood is expected to be of influence, it was measured at all objects at three randomly selected positions using a humidity sensor (KG 28816 Stuhr, Germany). The experiments described in this report studies one factor at a time while keeping others fixed.

2.1.1 Wooden axles

The factor ‘roundness of stems’ fluctuate to a large extent. In other words, some stems are rather circular while others are more oval shaped. Wooden sticks —exceptionally round compared to stems— were used to keep the factor ‘roundness of stems’ fixed. Pine-wood (*Pinus silvestrus*) sticks with a length of 2800 mm each and diameters of 11, 22, and 44 mm were cut into axles with lengths of 100±10 mm each (Fig. 1).

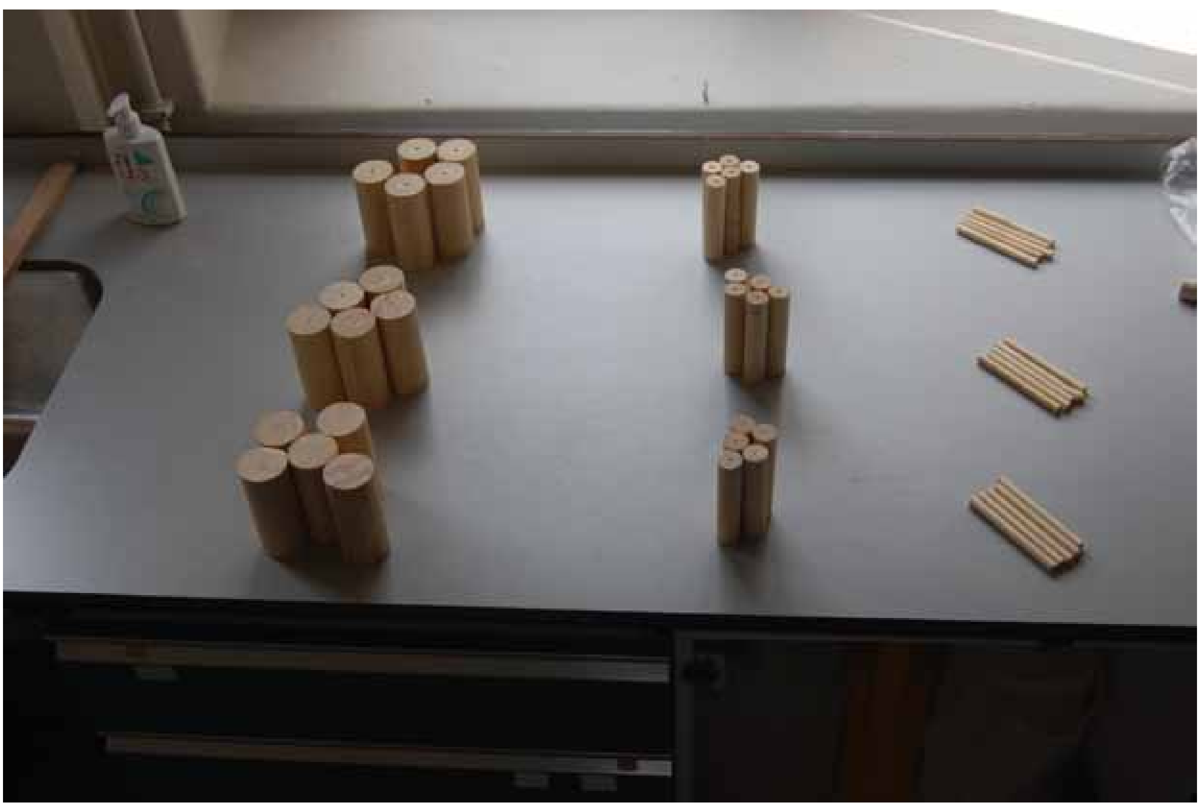

Fig. 1 Wooden axles with different outer diameters

2.1.2 Stems

Besides axles, main stems of Japanese maple (*Acer palmatum*) were analysed by X-ray (Fig. 2).

Fig. 2 Main stems of Japanese maple

2.1.3 Intact trees

Besides wooden axles and stems of Japanese maple, also intact Japanese maple trees (Acer palmatum) were analysed using an X-ray inspection system. Maple trees were part of a consignment which was found to be infested by long-horned beetles upon entry. The trees were 500±200 mm in length. The diameter of the stems was 25±10 mm.

2.2 X-ray inspection system

X-ray images were recorded on a luggage X-ray inspection system (Hi-Scan 6040i; Smiths Heimann, Germany). Such systems are commonly used on airports for inspection of luggage. The X-ray tube —source of the electromagnetic radiation— was located on the right side of the system underneath the conveyor. Tape was used to fix the wooden axles, stems, and trees on the conveyer (Fig. 3). The conveyor speed was approximately 0.2 m/s. The tunnel dimensions are 620 mm (W) x 418 mm (H). The anode voltage of the X-ray generator was approximately 140 kV.

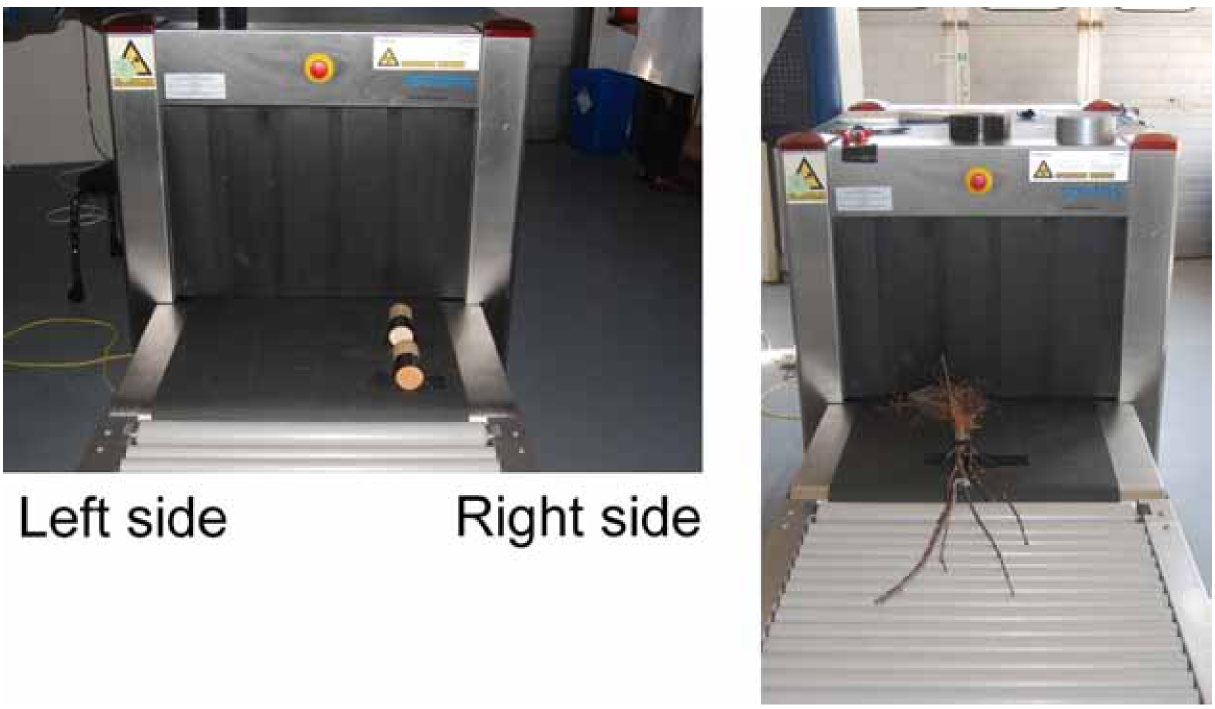

Fig. 3 X-ray inspection system with a pre-drilled wooden axles or an intact tree fixed on the conveyer by tape

2.3 Visual assessment of X-ray images

Visual assessment of the X-ray images was done to assess whether boreholes could be seen. No filters such as contrast enhancement, or colour inversion were applied. The images were displayed on a 17” monitor for visual assessment.

Visual assessment resulted in a number of:

1. True positive; in this case the tree is marked as suspicious. After destructive assessment it is confirmed that the tree contains one or more boreholes.

2. True negative; in this case the tree is marked as unsuspicious. After destructive assessment it is confirmed that the tree does not contain any borehole.

3. False positives; in this case the tree is marked as suspicious. After destructive assessment , it turns out that the tree does not contain any borehole.

4. False negatives: in this case the tree is marked as unsuspicious. After destructive assessment, it turns out that the tree contains one or more boreholes.

Visual assessment was evaluated by the number of true positives, true negatives, false positives and false negatives.

2.4 Machine vision

Besides visual assessment of the X-ray images, machine vision was applied on the X—ray images. These images were stored on the X-ray system in HIF format (Heimann Image Format). The images were converted to BMP (bitmap format) by OTS-Link (STI Security Training International, Wiesbaden, Germany). To convert the RGB image into a gray scale image, the three channels of the RGB image were transformed by Equation 1:

$$gray = 0.299 \times red + 0.587 \times green + 0.114 \times blue \qquad \text{Equation 1}$$

To detect holes in the grey scale images, a hole detection method was developed. The core of this method consisted of an algorithm to extract curvilinear structures and their widths from digital images. The applied technique was based on a line detection method, available in Halcon v. 9.0.1 (MVTec Software GmbH, Munich, Germany).
The extraction was done by using partial derivatives of a Gaussian smoothing kernel to determine the parameters of a quadratic polynomial in x and y for each point of the image (Steger, 1996). The parameter Sigma determines the amount of smoothing to be performed. The parameters of the polynomial are used to calculate the line direction for each pixel. Pixels which exhibit a local maximum in the second directional derivative perpendicular to the line direction are marked as line points. The line points found in this manner are then linked to contours. This is done by immediately accepting line points that have a second derivative larger than High. Points that have a second derivative smaller than Low are rejected. All other line points are accepted if they are connected to accepted points by a connected path. The pre-drilled stems were used to optimise the parameters Sigma, Low and High. The intact trees were used to test the optimised hole detection method. Constrains were applied to reduce the frequency of false positives. The first constrain applied was that boreholes have to be orientated nearly parallel to the centre line of the main stem (the angle was limited to +45° till -45°). The second constrain applied was that holes have to be more than 10 pixels in length.

Machine vision resulted in a number of:

1. True positive; in this case one or more boreholes are detected. After destructive assessment it is confirmed that the tree contains one or more boreholes.

2. True negative; in this case no borehole is detected. After destructive assessment it is confirmed that the tree does not contain any borehole.

3. False positives; in this case one or more boreholes are detected. After destructive assessment , it turns out that the tree does not contain any borehole.

4. False negatives: in this case no borehole is detected. After destructive assessment, it turns out that the tree contains one or more boreholes.

Visual assessment was evaluated by the number of true positives, true negatives, false positives and false negatives.

2.5 Destructive assessment

After X-ray analysis, the intact trees were cut into pieces of 20±10 mm to determine the number of boreholes per tree (Fig. 4).

Fig. 4 Wood pieces after destructive assessment to determine the number of boreholes per tree

3 Experiments

3.1 Experiment 0: Optimisation of the hole detection method

The pre-drilled stems were used to optimise the parameters Sigma, Low and High. An example of this optimisation procedure is provided in Fig. 5.

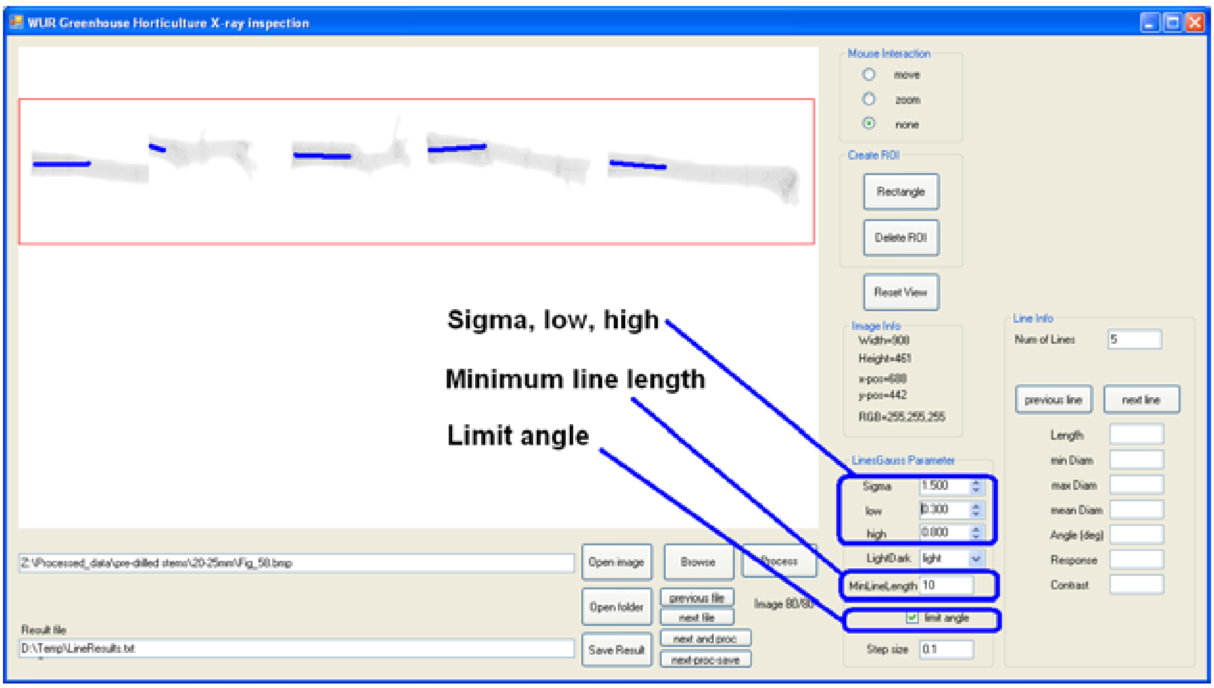

Fig. 5 Optimisation of the hole detection method. This X-ray image is derived from pre-drilled stems with an outer diameter of 25±10 mm. The holes were 5 mm in diameter and drilled into the centres of the stems. In this example, the 5 pre-drilled holes were detected.

3.2 Experiment 1: The effect of object position

In the X-ray system used, the electromagnetic radiation was emitted by the X-ray tube, located on the right side of the system underneath the conveyor. As a result, the object position on the conveyer may have an effect on the detectability of bore holes. Experiment 1 was done to evaluate this aspect. A stem with a length of about 200 mm containing a borehole was positioned on the conveyer at respectively 100, 200, 300, 400 or 500 mm of the right. The effect of object position was determined by visual assessment and machine vision.

3.3 Experiment 2: The effect of boredust

As a result of larvae, holes may be filed with boredust (Fig. 6). Perhaps, this boredust effects the detectability of such holes. Experiment 2 was done to evaluate the effect of boredust on the detectability of boreholes. For this experiment, five stems with a diameter between 30-35 mm were randomly selected. Holes with a diameter of 5 mm were drilled into the centre of these stems. X-ray images of these stems were made before and after filling the holes with boredust. The effect of boredust on the detectability of holes was determined by visual assessment.

Fig. 6 Borehole filled with boredust. This picture is derived from one of the X-ray analysed trees. The corresponding X-ray image is provided in Fig. 8. This borehole contained a larva of the long-horned beetle.

3.4 Experiment 3: The effect of wood humidity

In practice, wood humidity differs to a great extent. Experiment 3 was done to study the effect of wood humidity on the detectability of holes. For this experiment, holes with a diameter of 5 mm were drilled into pine-wood axles with outer diameters of 22 and 44 mm. These axles were soaked in water for 12 h. X-ray images of these stems were made before and after soaking the axles. The effect of wood humidity on the detectability of holes was determined by visual assessment.

3.5 Experiment 4: The effect of axle diameter, hole diameter and hole position

In practice, the factors stem diameter, hole diameter, and hole position fluctuate to a large extent. Wooden axles were used in Experiment 4 to study these factors under controlled conditions. For this experiment, holes were drilled either in the centre of the axial side (Fig. 7A), or at ¼ of the centre line (Fig. 7B) with one hole per axle. Diameters of these holes were 1, 2, 3, or 5 mm. The depth of the holes was 30-50 mm. Wooden axles with holes drilled at ¼ of the centre line were X-ray analysed three times, at three different positions (Fig. 7B-D). So, per diameter of the hole, four states occurred: state A, B, C and D.

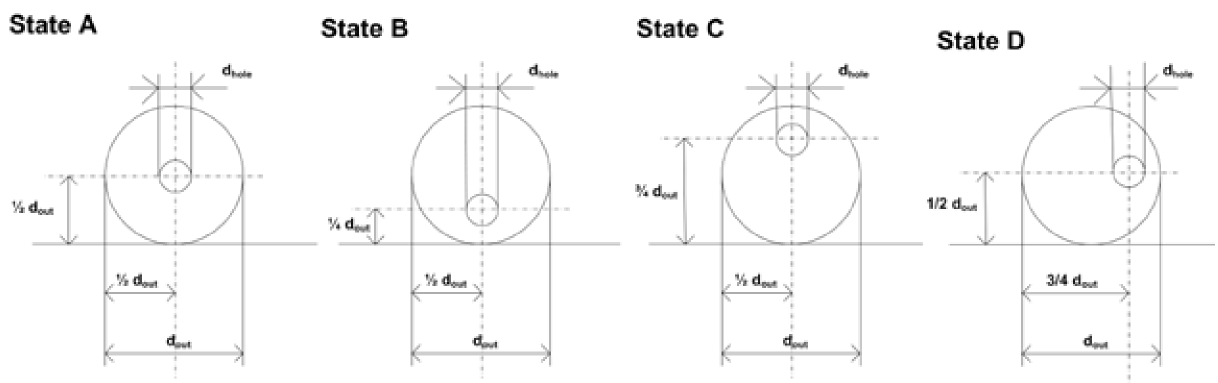

Fig. 7 Four states in which wood axles were X-ray analysed: state A, B, C and D. Outer diameter of the axle (d_{out}), the diameter of the hole (d_{hole}) and the positions of the pre-drilled holes are provided per state.

In total, 195 pre-drilled axles were prepared and subsequently numbered. An overview of these axles is provided in Table 1.

Table 1. Outer diameter (d_{out}), diameter of hole (d_{hole}), and the state of the axle

Number	**d_{out} [mm]**	**d_{hole} [mm]**	**State***	**Replicates**
1-5	44	5	A	5
6-10	44	3	A	5
11-15	22	5	A	5
16-20	22	3	A	5
21-25	9	5	A	5
26-30	9	3	A	5
31-35	44	1	A	5
36-40	22	1	A	5
41-45	9	1	A	5
46a-50a	44	5	D	5
46b-50b	44	5	B	5
46c-50c	44	5	C	5
51a-55a	44	3	D	5
51b-55b	44	3	B	5
51c-55c	44	3	C	5
56a-60a	44	1	D	5
56b-60b	44	1	B	5
56c-60c	44	1	C	5
61a-65a	22	5	D	5
61b-65b	22	5	B	5
61c-65c	22	5	C	5
66a-70a	22	3	D	5
66b-70b	22	3	B	5
66c-70c	22	3	C	5
71a-75a	22	1	D	5
71b-75b	22	1	B	5
71c-75c	22	1	C	5
76a-80a	12	5	D	5
76b-80b	12	5	B	5
76c-80c	12	5	C	5
81a-85a	12	3	D	5
81b-85b	12	3	B	5
81c-85c	12	3	C	5
86a-90a	12	1	D	5
86b-90b	12	1	B	5
86c-90c	12	1	C	5
91-95	44	2	A	5
96-100	22	2	A	5
101-105	11	2	A	5
Total				195

*States are provided in Fig. 7

3.6 Experiment 5: The effect of stem diameter, hole diameter and hole position

In addition to drilling well-defined holes into axles (Experiment 4), holes were also drilled into stems to mimic real world conditions. Experiment 5 was done to study the effect of stem diameter, hole diameter and hole position on the detectability of such holes under such conditions. For this experiment, the stems were divided into two groups. Group 1 consisted of stems with a length of 50±5 mm and outer diameters of 40-45 mm. These stems were retrieved from the wood collection of the PD. Group 2 consisted of stems with a length of 200±50 mm and outer diameters of 20-25 mm. These stems were retrieved from maple trees which were part of a consignment which was found to be infested by long-horned beetles upon entry.

Holes were drilled into these stems with one hole per stem. Diameters of these holes were 1, 2, 3, or 5 mm. The depth of the holes was 30-50 mm. Holes were drilled either in the centre of the axial side, or at ¼ of the centre line. In total, 125 pre-drilled stems were prepared and subsequently numbered. An overview of these stems is provided in Table 2. The effect of stem diameter, pre-drilled hole diameter and hole position on the detectability of holes was determined by visual assessment.

Table 2. Outer diameter (d_{out}), diameter of hole (d_{hole}) and the state of the pre-drilled stems used in the experiments

	Number	d_{out} [mm]	d_{hole} [mm]	State*	Replicates
Group 1	1a-5a	35-40	5	B	5
	1b-5b	35-40	5	C	5
	1c-5c	35-40	5	D	5
	6a-10a	35-40	3	B	5
	6b-10b	35-40	3	C	5
	6c-10c	35-40	3	D	5
	11a-15a	35-40	2	B	5
	11b-15b	35-40	2	C	5
	11b-15b	35-40	2	C	5
	16-20	35-40	5	A	5
	21-25	35-40	3	A	5
	26-30	35-40	2	A	5
Group 2	212a, 199a, 102a, 206a, 22a	20-25	5	C	5
	212b, 199b, 102b, 206b, 22b	20-25	5	D	5
	212c, 199c, 102c, 206c, 22c	20-25	5	B	5
	121,381,372,139,316	20-25	5	A	5
	293a, 380a, 90a, 100a, 354a	20-25	3	C	5
	293b, 380b, 90b, 100b, 354b	20-25	3	D	5
	293c, 380c, 90c, 100c, 354c	20-25	3	B	5
	165, 314, 305, 553, 136	20-25	3	A	5
	455a, 48a, 287a, 364a, 363a	20-25	2	C	5
	455b, 48b, 287b, 364b, 363b	20-25	2	D	5
	455c, 48c, 287c, 364c, 363c	20-25	2	B	5
	542, 308, 301, 502, 438	20-25	2	A	5
	3, 15, 355, 12, 205, 3	20-25	1	B	5
	Total				125

*States are equal to those for wooden axles; provided in Fig. 7

3.7 Experiment 6: Detectability of holes in intact maple trees

Pre-drilled holes are not same to larvae induced holes. Perhaps, such ‘real’ holes vary in diameter and position within one single stem. Experiment 6 was done to evaluate this aspect. In total, 929 intact trees were X-ray analysed for this experiment. The detectability of holes in intact maple trees was determined by visual assessment and machine vision.

4 Results

4.1 Experiment 0: Optimisation of the hole detection method

The accuracy of the hole detection method depends on three parameters: Sigma, High and Low. Optimal settings for these parameters for pre-drilled stems are provided in Table 3.

Table 3. Optimal settings of the hole detection method for pre-drilled stems. Outer diameters (d_{out}), diameters of hole (d_{hole}) and the states of the pre-drilled stems are provided in Table 2.

	Number	Sigma	High	Low
Group 1	1a-5a	1.9	.1	.8
	1b-5b	1.5	.35	1.0
	1c-5c	1.4	.20	1.2
	6a-10a	1.3	.23	.9
	6b-10b	1.7	.33	.8
	6c-10c	1.6	.45	1.0
	11a-15a	1.7	.13	2.1
	11b-15b	1.4	.22	2.0
	11b-15b	1.2	.11	1.0
	16-20	1.25	.55	2.7
	21-25	1.9	.1	.8
	26-30	1.5	.35	1.0
	Average	1.53	.3	1.3
Group 2	212a, 199a, 102a, 206a, 22a	1.4	.2	.7
	212b, 199b, 102b, 206b, 22b	1.3	.23	.8
	212c, 199c, 102c, 206c, 22c	1.7	.33	.8
	121,381,372,139,316	1.6	.35	1
	293a, 380a, 90a, 100a, 354a	1.9	.41	.8
	293b, 380b, 90b, 100b, 354b	1.5	.35	.9
	293c, 380c, 90c, 100c, 354c	1.4	.2	.9
	165, 314, 305, 553, 136	1.3	.23	.7
	455a, 48a, 287a, 364a, 363a	1.7	.13	.8
	455b, 48b, 287b, 364b, 363b	1.6	.15	1
	455c, 48c, 287c, 364c, 363c	1.7	.13	.9
	542, 308, 301, 502, 438	1.4	.12	.9
	3, 15, 355, 12, 205, 3	1.4	.2	.7
	Average	1.5	.3	.8

4.2 Experiment 1: The effect of object position on the detectability of boreholes

4.2.1 Visual assessment

The position of an object on the conveyer had a large effect on the visual appearance of boreholes in stems. Most close to the X-ray tube, at 100 mm from the right side of the conveyer, the images appeared to be stretched out in y-direction. Most far from the X-ray source, at 500 mm from the right side of the conveyer, the images appeared to be compressed (Fig. 8).

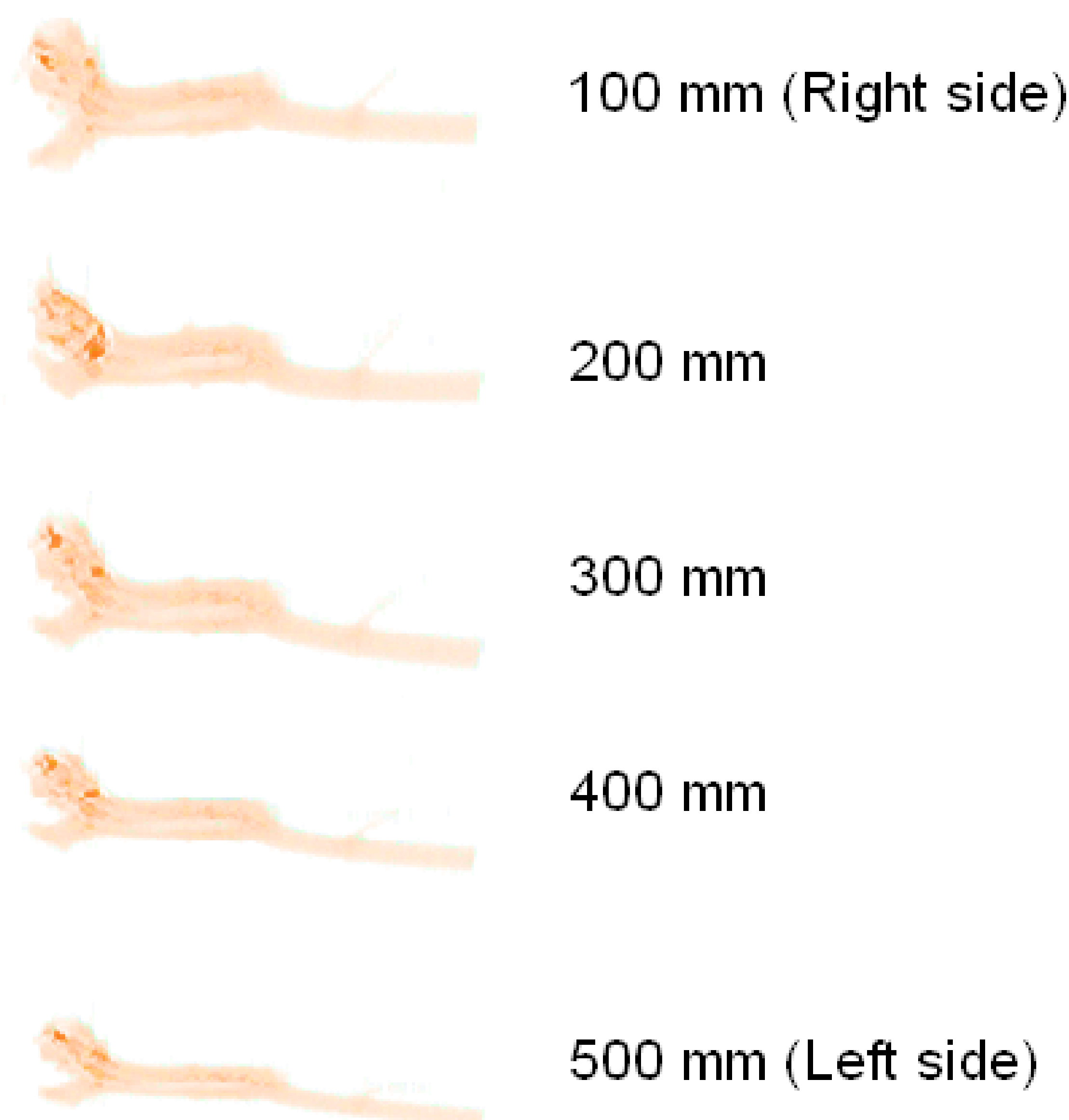

Fig. 8. The effect of stem position on the detectability of boreholes. Most close to the X-ray source, at 100 mm from the right side of the conveyer, the images appeared to be stretched out in y-direction. Most far from the X-ray source, at 500 mm from the right side of the conveyer, the images appeared to be stretched in. Left and right side are clarified in Fig. 3.

4.2.2 Machine vision

Boreholes could be detected by machine vision, independent on the position of the tree on the conveyer (Fig. 9). Besides boreholes, a number of false positives was detected. This number of false positives depended on the position of the tree on the conveyer (Fig. 9).

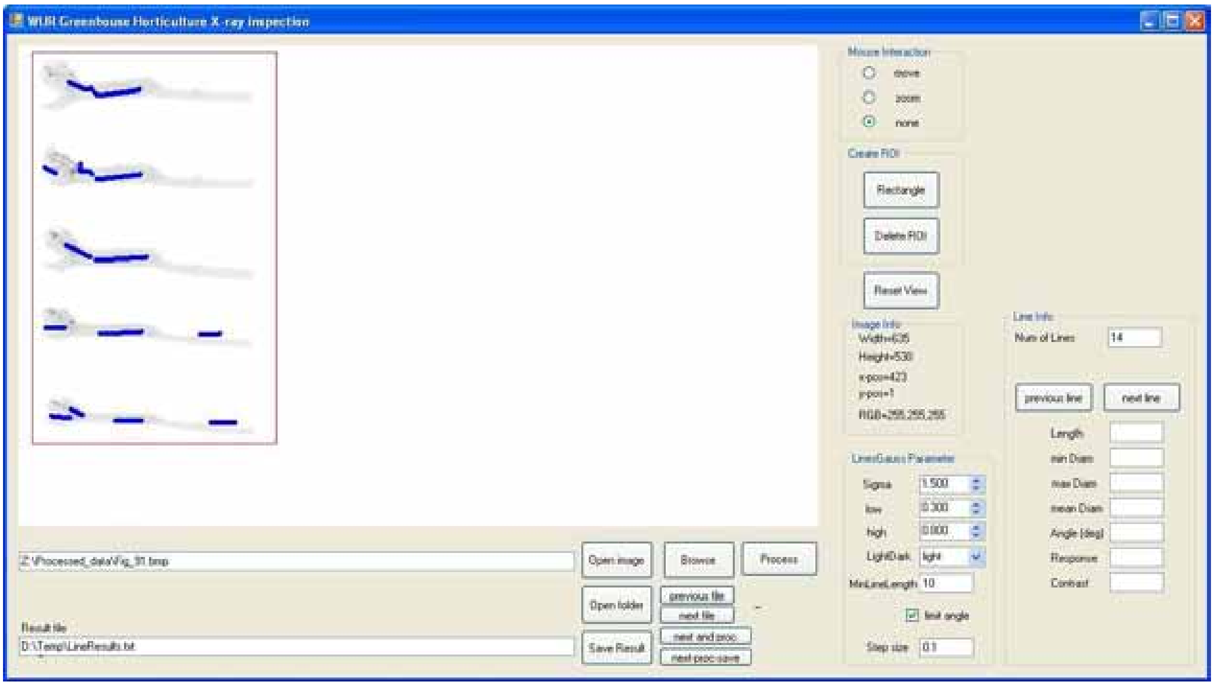

Fig. 9. Detection of boreholes by machine vision. The corresponding X-ray image is provided in Fig. 8. Besides boreholes, a number of false positives was detected.

4.3 Experiment 2: the effect of boredust

The presence of boredust did not seem to have a large effect of the visual appearance of boreholes in X-ray images (Fig. 10). In both cases, pre-drilled holes of 5 mm were clearly visible.

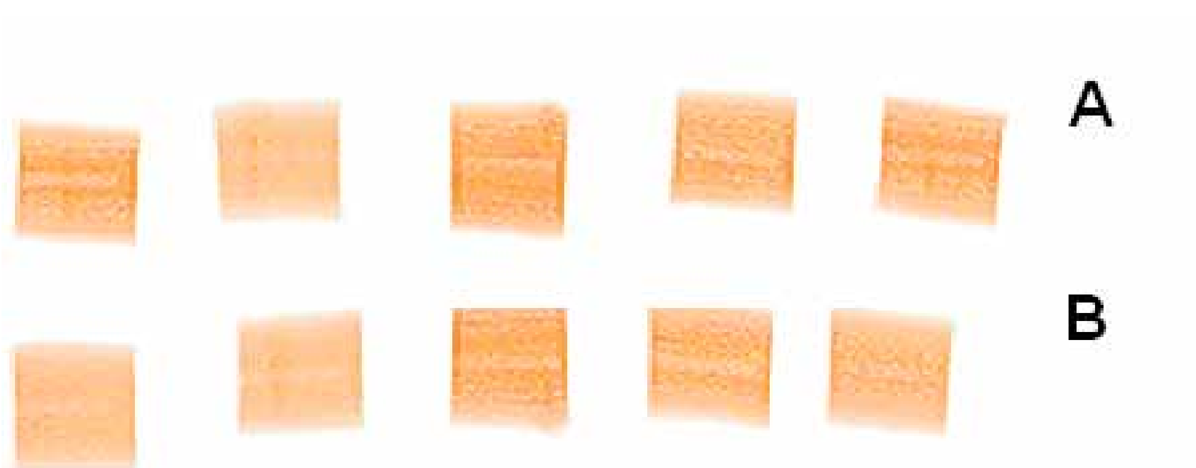

Fig. 10. The effect of boredust on the visual appearance of boreholes in X-ray images. Images are retrieved from maple stems with outer diameters of 30-35 mm containing pre-drilled holes of 5 mm: A) holes without boredust, B) same stems but holes filled with boredust

4.4 Experiment 3: The effect of wood humidity

Before soaking, the humidity of the wood was below 6%. After soaking ,the humidity of the wood was above 24%. This difference of wood humidity seemed to had a slight effect on the visibility of pre-drilled holes in pine-wood axles (compare Fig. 11A with Fig. 11B). This slight effect seemed to be independent of the outer diameter of the axle (compare Fig. 11A and Fig. 11B with Fig11C and Fig 11D). This slight effect seemed to be independent of the diameter of the hole and the position of the hole (data not shown).

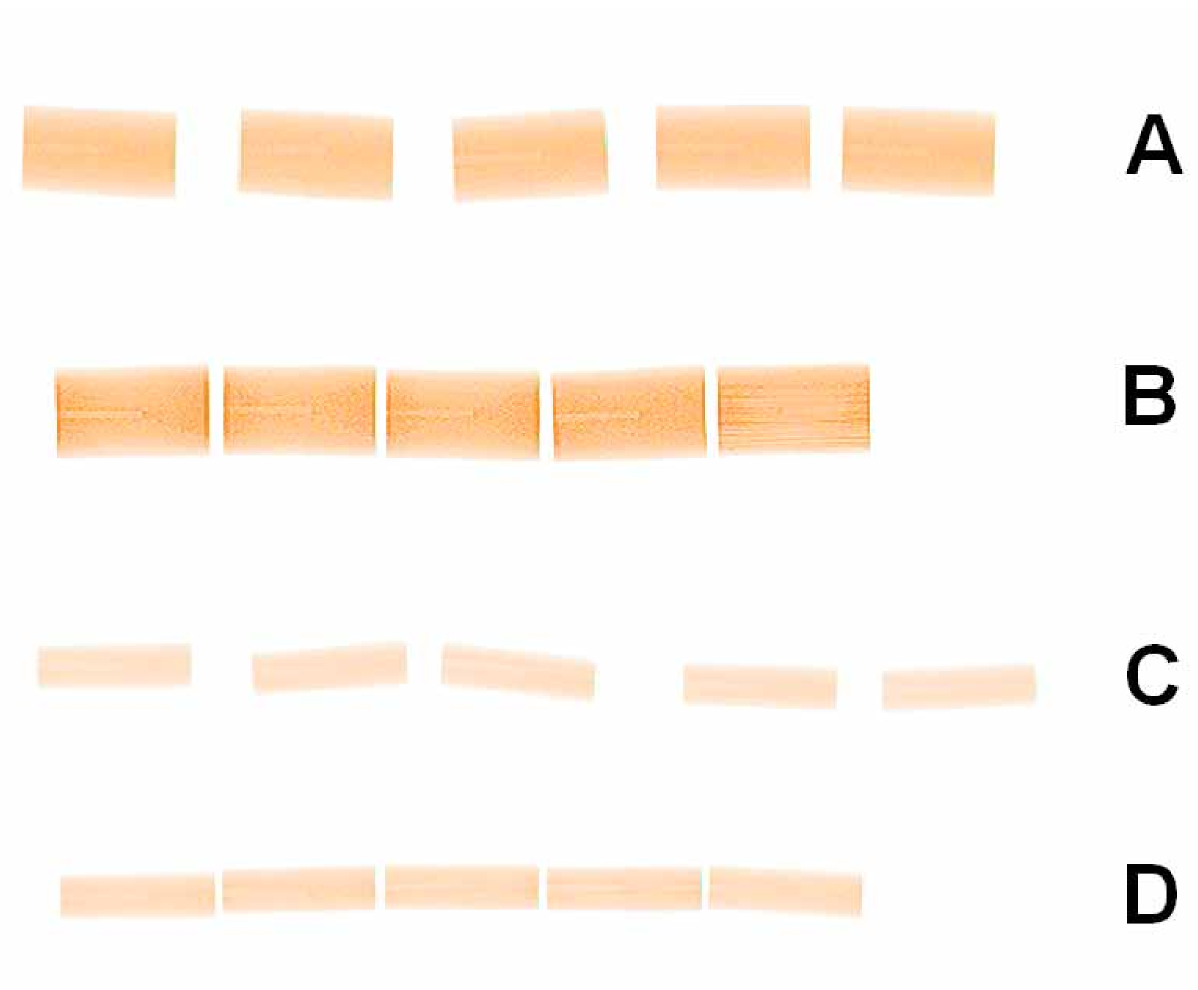

Fig. 11. The effect of wood humidity on the visual appearance of pre-drilled holes in pine-wood axles. A) d_{out} = 44 mm, d_{hole} = 5 mm, wood humidity = 6%; B) d_{out} = 44 mm, d_{hole} = 5 mm, wood humidity > 24%; C) d_{out} = 22 mm, d_{hole} = 5 mm, wood humidity = 6%; D) d_{out} = 22 mm, d_{hole} = 5 mm, wood humidity > 24%

4.5 Experiment 4: The effect of axle diameter, pre-drilled hole diameter and hole position

In all cases, holes with a diameter of 5 mm were visible on the X-ray images (Fig. 12A and Fig. 12B). Holes with a diameter of 3 mm could just be seen (Fig. 12C). Holes with a diameter of 2 mm were invisible on the X-ray images. The axle diameter (compare Fig. 12A with Fig. 12B) as well as the position (State) of the hole (compare Fig. 12B with Fig. 12D) seem to have an effect on the visibility of these holes.

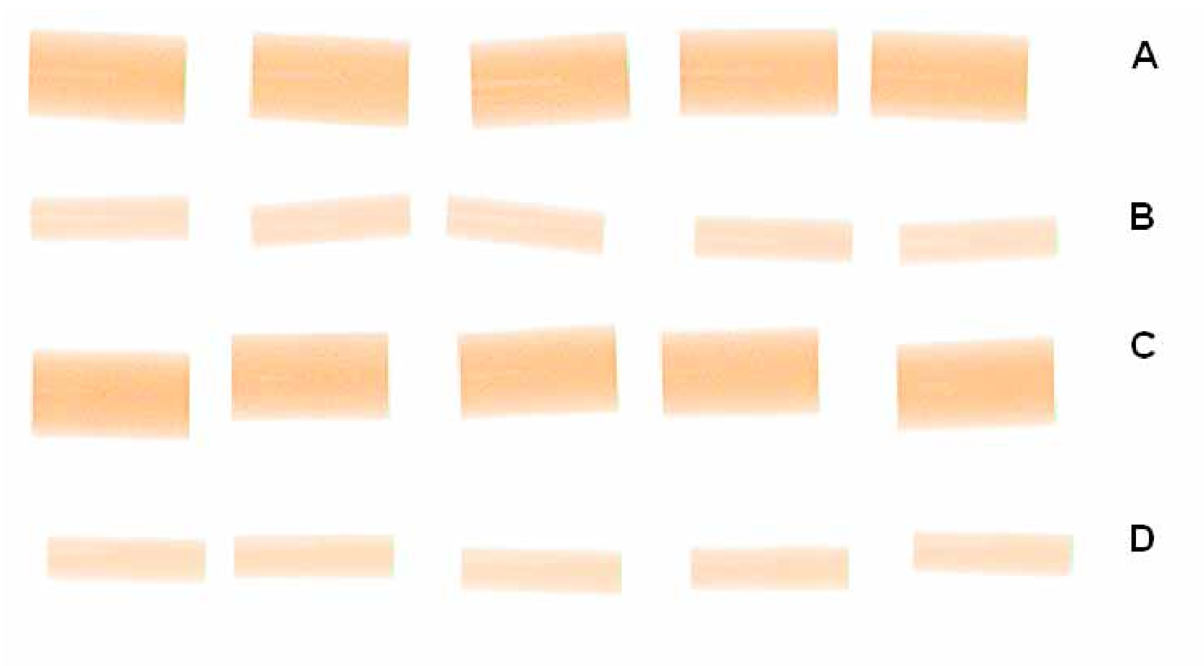

Fig. 12. The effect of axle diameter, pre-drilled hole diameter and hole position on the visual appearance of boreholes in X-ray images. A) d_{out} = 44 mm, d_{hole} = 5 mm, State = A; B) d_{out} = 22 mm, d_{hole} = 5 mm, State = A; C) d_{out} = 44 mm, d_{hole} = 3 mm, State = A; D) d_{out} = 22 mm, d_{hole} = 5 mm, State = D.

4.6 Experiment 5: The effect of stem diameter, pre-drilled hole diameter and hole position

For this experiment, two diameter-groups were used. Group 1 consisted of stems with outer diameters of 30-35 mm. Group 2 consisted of stems with outer diameters of 20-25 mm. In both groups, pre-drilled holes with a diameter of 5 mm were visible on the X-ray images (Fig. 13A and Fig. 13B). To some extent, pre-drilled holes with a diameter of 3 mm were visible on images from both groups (Fig. 13C). Holes with a diameter of 2 mm were invisible on the X-ray images (data not shown). The stem diameter (Compare Fig. 13A with Fig. 13B) as well as the position of the hole (Compare Fig. 13B with Fig. 13D) seem to have an effect on the visibility of these holes.

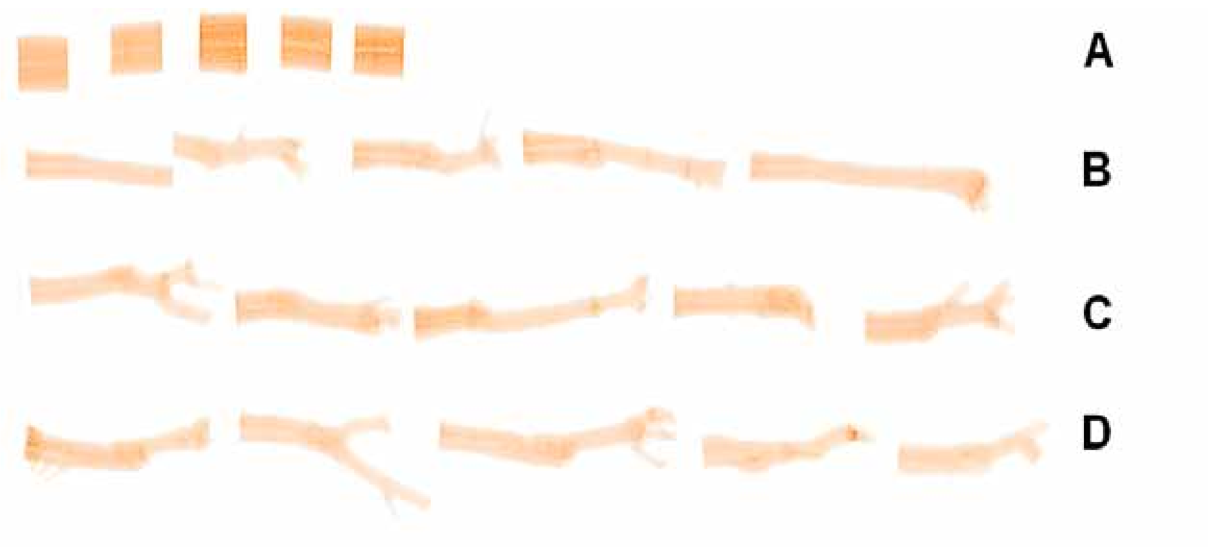

Fig. 13. The effect of stem diameter, pre-drilled hole diameter and hole position on the visual appearance of boreholes in X-ray images. A) d_{out} = 30-35 mm, d_{hole} = 5 mm, State = A; B) d_{out} = 20-25 mm, d_{hole} = 5 mm, State = A; C) d_{out} = 20-25 mm, d_{hole} = 3 mm, State = A; D) d_{out} = 20-25 mm, d_{hole} = 5 mm, State = D.

4.7 Experiment 6: Detectability of holes in intact maple trees

4.7.1 Visual assessment

After visual assessment of the 929 X-ray images, 5 trees were marked as suspicious. In these cases, the suspicious areas were located in the main stem. After X-ray images were made, all trees were cut into pieces of 20-25 mm to determine the number of boreholes. This destructive assessment confirmed that three of the suspicious trees contained boreholes (Fig. 14). Whether or not these boreholes were the result of long-horned beetles could not be confirmed. One suspicious tree turned out to contain holes caused by rot (Fig. 15). A second suspicious tree turned out to contain no hole at all; probably a hole was detected because this tree contained a groove in the stem. The destructive assessment also resulted in the detection of a borehole which was initially unseen on the X-ray images, but seen after doing visual assessment of the X-ray image once more. Whether or not this borehole was the result of a long-horned beetle could not be confirmed. A summary of the results of visual assessment is provided in Table 4.

Table 4. Number of true positives, true negatives, false positives and false negatives as a result of visual assessment

Classification	Nr.	Remark
True positives	3	Whether or not the result of longhorned-beetles could not be confirmed
True negatives	923	
False positives	2	One was caused by rot. The other one was probably caused by a groove in the stem
False negatives	1	But seen after careful inspection of the X-ray image. Hole certainly not the result of long-horned beetle

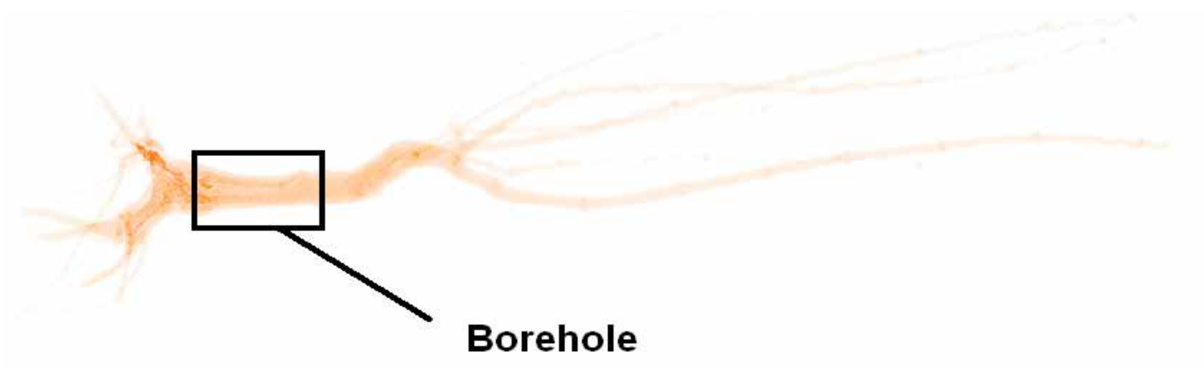

Fig. 14. X-ray image of an intact maple tree marked as suspicious. After destructive assessment, it was confirmed that this tree contained a borehole in the main stem.

Fig. 15. X-ray image of an intact maple tree marked as suspicious. After destructive assessment of this tree, the hole turned out to be caused by rot.

4.7.2 Machine vision

In order to detect boreholes in inact trees, the average Sigma, High and Low values from Group 2 (Table 3) were implemented into the hole detection method. Based these values and applying machine vision on the 929 X-ray images of intact trees, a total of 3 true positives and 26 true negatives was detected. An example of a true positive is provided in Fig. 16. Furthermore, a total of 899 false positives was detected. These false positves were mainly the result of lines (in total 5966) detected in the rootzone and crown of the trees. The hole caused by rot was also detected by machine vision (Fig. 17). Also one false negatives was detected. The borehole belonging to this false negative was not the result of a long-horned beetle. A summary of the results of machine vision is provided in Table 5.

Table 5. Number of true positives, true negatives, false positives and false negatives as a result of machine vision

Classification	**Nr.**	**Remark**
True positives	3	Whether or not the result of longhorned-beetles cannot be confirmed
True negatives	26	
False positives	899	Mainly the result of line detected in the rootzone and crown. Hole caused by rot also detected.
False negatives	1	Hole was not the result of a long-horned beetle

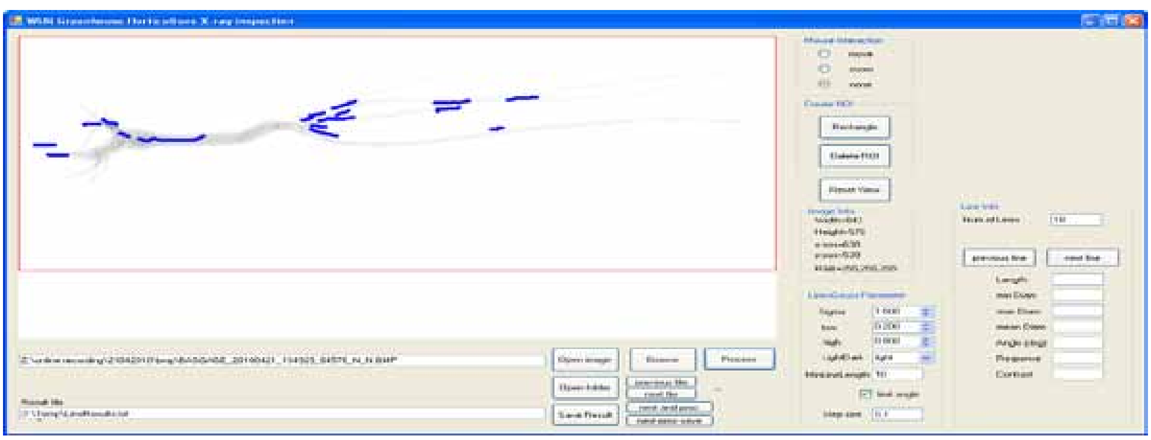

Fig. 16. Detection of a borehole by machine vision. Besides this hole, also 17 holes were recognised — in this case especially in the crown — which were actually no holes.

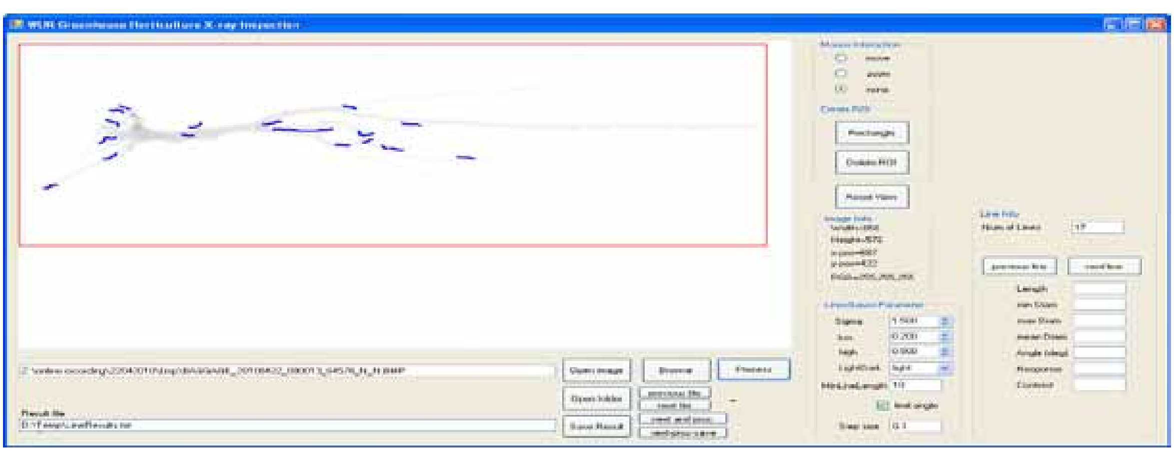

Fig. 17. Detection of a hole caused by rot by machine vision. Besides this hole, also 16 holes were recognised which were actually no holes.

5 Discussion

The first objective of this study was to determine whether X-ray can be used to visualise boreholes in intact trees. Visual assessment of the X-ray images was done by a human. But human observations are subjective. Further research should increase the number of observers to determine the inter-observer variability after visual assessment of X-ray images. As mentioned before, the visual assessment by human is subjective. Probably, training of X-ray operators will improve the detectability of holes. Digital filters such as contrast enhancement or colour inversion will probably also improve the visual assessment of X-ray images. However, the effect of such filters on the visual assessment of X-ray images has not been tested in the present study. In future research, the effect of such filters should be tested.

The second objective of this study was to determine the ability of machine vision to detect boreholes in intact trees. To achieve this objective, a machine vision application was made. The boreholes detected by destructive assessment were also detected in intact trees by this application (Fig. 9 and Fig. 16). Besides these boreholes, the machine vision application also identified a large number of boreholes which actually were no boreholes (false positives). The frequency of false positives would probably reduce when a 2-step machine vision approach would be used: first detect the regions containing roots and crown, then exclude these regions when searching for holes. Since most false positives were located in the root zone and crown, this would definitely reduce the frequency of false positives. The frequency of false positives would also reduce in case a-priori information about the trees is used. For instance: the optimal settings for the hole detection method depended on the outer diameter, the diameter of the hole and the position of the hole (Table 3). Before X-ray inspection, the outer diameter of the stems could be measured. Results of these measurements could then be used to adapt the optimal settings according to the trees under inspection.

The third objective of this study was to determine the effect of tree position, presence of boredust, wood humidity, outer diameter of the stem, diameter of the hole, and hole position on the visibility of boreholes in intact trees. The presence of bore dust had only a slight effect on the detectability. Apparently, the density of boredust is small compared to wood. The fact that boreholes are detectable –independent of the presence of boredust– is advantageous since boredust is expected to be common. Also the effect of wood humidity (6 % *versus* 24%) had only a slight effect on the detectability of holes. This can be explained because differences in density in the order of 10% cannot be detected with the X-ray setup used in this study. The X-ray penetrating ability depends on the density of the object. In the present study, maple trees were used. However, the density of wood not only depends on its humidity, but also depends on the tree species. As a result, the contrast between wood and borehole may depend on tree species. Other tree species should therefore be analysed to test the effect of it on the detectability of holes. In this research, the effect of the horizontal position of the tree on the detectability of was studied. In further research, also the effect of vertical position should be studied.

In the present study, an X-ray system was used which was optimised for discriminating high density materials such as steel (density = 7-8 g/cm^3) from low density materials such as cotton (density = 1-2 g/cm^3). Almost certainly, such a system is not optimised for discriminating boreholes (density = 0 g/cm^3) from regular wood materials (density = 0.7-1.4 g/cm^3). Further research should include X-ray systems which are optimised for this purpose. If not commercially available, such system should be developed. When developing an X-ray system for detection of boreholes, also the resolution should be considered. The X-ray system used in this study produced images with a resolution of 1 mm. If the system could produce images with a higher resolution, the detectability of boreholes would improve. Furthermore, higher resolution images might allow the detection of long-horned beetle eggs. Currently, X-ray inspection systems with higher resolution are available on the market. For instance X-ray systems which are designed for medical examination. Such systems are currently able to produce images with a resolution of 0.1 mm. There are several companies that manufactures high resolution X-ray systems for medical examination. These companies have a lot of experience with X-ray systems and machine vision. In case of further research, it is recommended to involve such companies and share experience.

Unfortunately, the number of real boreholes was limited in the trees under investigation. We recommend to obtain trees with real boreholes and to use them for X-ray analysis in further research.

Intact trees were cut into pieces of 20-25 mm to determine the number of boreholes Although such destructive assessment is probably the most suitable method, it is questionable whether small (diameter < 1 mm, length < 20 mm) boreholes are detectable this way.

6 Conclusions and future directions

Based on visual inspection of X-ray images, boreholes in intact trees are detectable. Besides these true positives, also holes were recognised which —after destructive assessment— were actually no holes (false positives). Finally, a borehole which was actually there, was undetected (false negatives). Likely, the number of true positives and true negatives will increase and the number of false positives and false negatives will decrease in case the X-ray operator is trained. Hence, we recommend to train X-ray operators to improve the detection of boreholes by visual inspection.

The boreholes detected by visual assessment were also detected by machine vision. However, machine vision also resulted in a number of false positives and false negatives. If an X-ray system will be developed that specifically aims at the detection of boreholes, the number of true positives will increase and the number of false positives and false negatives will decrease. If such a borehole specific X-ray instrument should be developed, we strongly recommend to involve companies that have experience in manufacturing X-ray systems. The number of false positives will probably also reduces in case the hole detection method is improved. A first priority in future research would be to detect and exclude regions that are unlikely to contain boreholes.

The 929 trees under X-ray investigation were part of a consignment of 20,000 trees which was found to be infested by long-horned beetles upon entry. When writing this report, it was decided to X-ray investigate another 3000 trees, part of the same consignment. We recommend to study the X-ray photos associated with those trees, especially photos in which boreholes of long-horned beetles seemed to be present. This aspect requires serious attention since several living larvae of long-horned beetles have been found in some of the 3000 trees.

Finally, it is recommended to study sensor-fusion: combining of sensory data from different types of sensors. For example, adding a digital camera to an X-ray system would result in high resolution pictures from the outside of the tree. These pictures can be analysed —visual or automatic— to search for the presence of additional symptoms of beetle infestation such as fly-out openings.

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