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Image Processing Approach for Detection of Three-Dimensional Tree-Rings from X-Ray Computed Tomography

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Abstract**—**Tree-ring analysis is an important part of the quality assessment and the dating of (archaeological) wood samples. It provides quantitative data about the whole anatomical ring structure, which can be used, for example, to measure the impact of the fluctuating environment on the tree growth, for the dendrochronological analysis of archaeological wooden artefacts and to estimate the wood mechanical properties. Despite advances in computer vision and edge recognition algorithms, detection and counting of annual rings are still limited to 2D datasets and performed in most cases manually, which is a time consuming, tedious task and depends strongly on the operator's experience. This work presents an image processing approach to detect the whole 3D tree-ring structure directly from X-ray computed tomography imaging data. The approach relies on a modified Canny edge detection algorithm, which captures fully connected tree-ring edges throughout the measured image stack and is validated on X-ray computed tomography data taken from six wood species.

Keywords**—**Ring recognition, edge detection, X-ray computed tomography, dendrochronology.

I. Introduction

TREE-ring analysis is crucial in the understanding, modelling and assessment of the evolution of the wood sample over time. It provides quantitative data about the whole anatomical ring structure, which can be used, for example, to measure the impact of the fluctuating environment on the tree growth at various geographical and time scales [1], to investigate impacts of rising atmospheric CO_2 concentrations [2], for the dendrochronological analysis of archaeological wooden artifacts [3] and to estimate the wood mechanical properties [4].

Tree-ring measurements have been traditionally performed manually, one-by-one by experts, using appropriated equipment, which is a quite cumbersome and time-consuming work [5]. Alternative methods use digital images of the specimen surface taken by digital cameras or scans and image-processing based algorithms for semi-automatic tree-ring boundaries recognition [6]-[10]. These methods, however, have been only applied to single 2D images and successful application requires proper treatment of the samples surface to remove impurities and unevenness, which becomes exceedingly difficult to do in the case of coated surfaces. In addition to that, they do not provide information about the 3D tree-ring morphology and they lack applicability in unique or highly gradated findings, where subsamples from the wood core are impossible or not allowed to be extracted.

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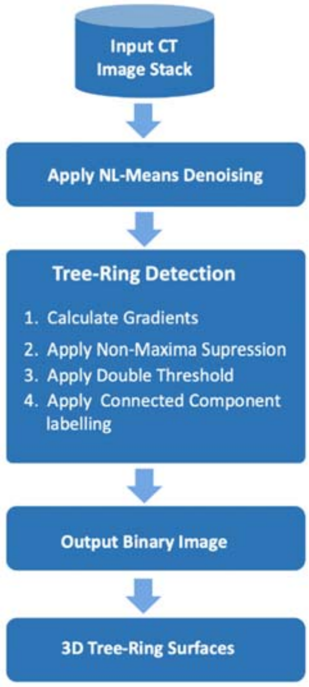

Fig. 1 The pipeline overview of the proposed approach

Expanding the tree-ring analysis to 3D imaging data is feasible using X-ray computed tomography (X-CT). X-CT is a powerful non-destructive technique which allows to inspect the 3D microstructure of a sample at different length scales [17]. By choosing an appropriated measurement protocol, morphological and physical information of the wood samples can be obtained at a large number of cross-sections, while preserving the integrity of the sample. By processing such information, numerical models of the sample can be developed to quantify the wood anatomy and properties [18]-[20].

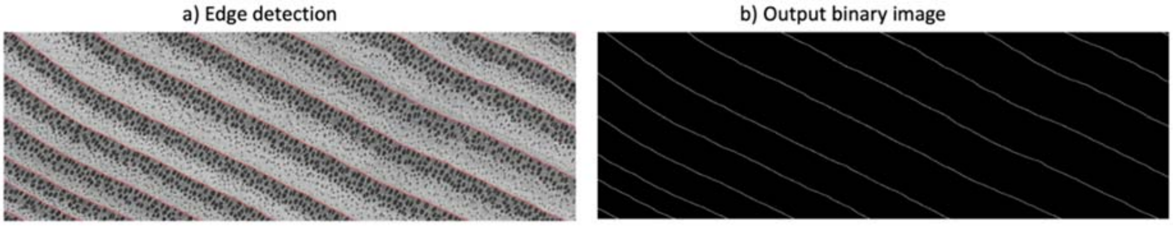

Fig. 2 Result of applying the developed edge-detector algorithm on a single X-CT slice of Ash: (a) Detected tree-ring edge boundaries (red lines), (b) Output binary image (white lines are edges) generated by the algorithm,

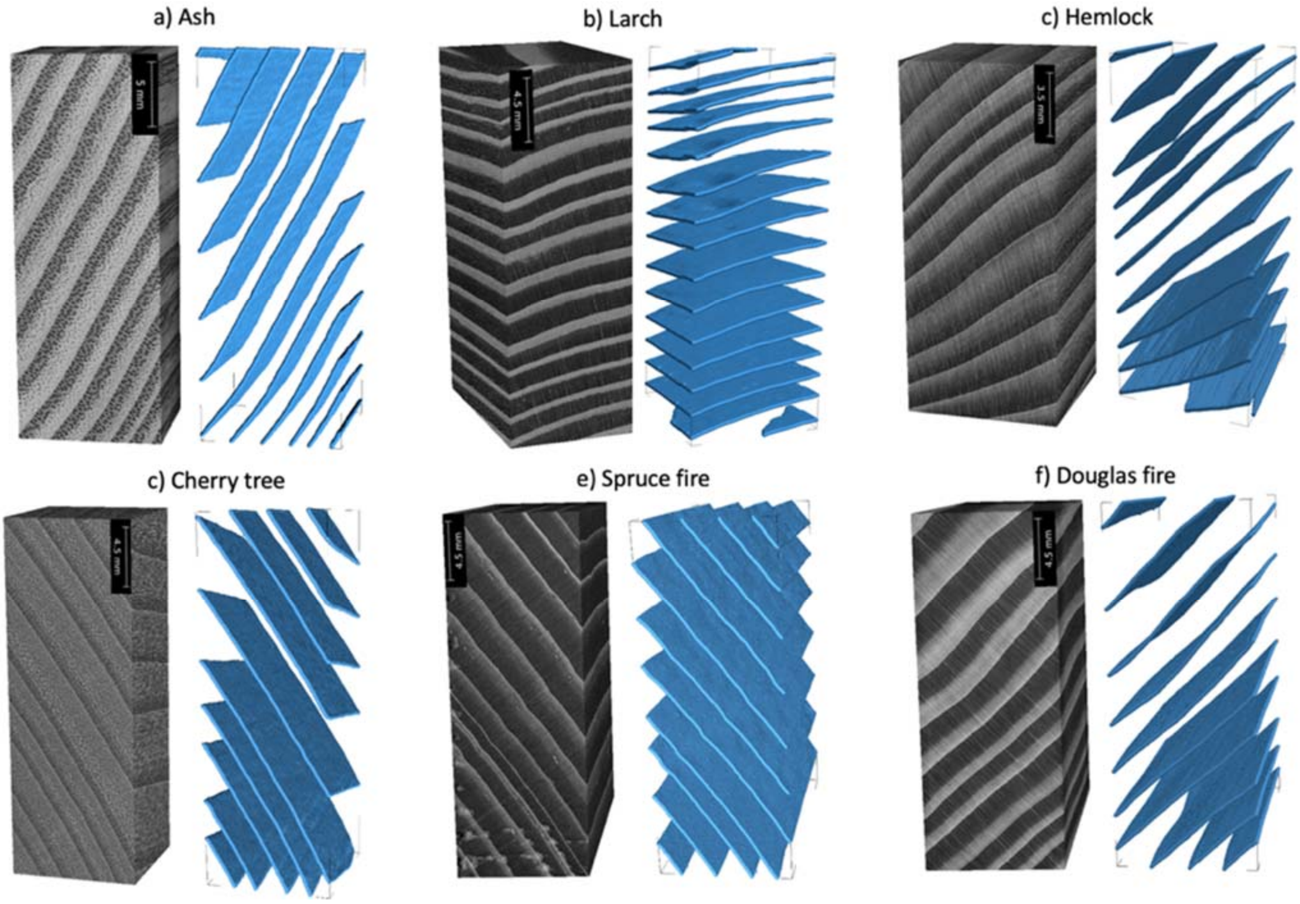

Fig. 3 The measured X-CT image stack and their calculated 3D tree-ring surfaces (plots in blue) for each wood specie studied

In this paper, an automated approach to recognize and quantify the tree-rings from volumetric X-CT imaging data is proposed. The applicability of the procedure is demonstrated by automatically extracting tree-ring surfaces from X-CT imaging data obtained from six different wood species.

II. The 3D Automated Approach

The present approach relies on a developed modified version of the Canny algorithm [11], [12] combined with edge-preserving filters, Otsu threshold, connected-component analysis and is fully implemented in Python 3.7. The main steps are illustrated in Fig. 1 and summarized in the following.

Image filtering: Noise in X-CT images may impede the recognition of structurers from the cross-sectional images. This noise appears during both measurements and reconstruction processes caused by multiple sources [17]. Therefore, image denoising at the beginning is a critical preprocessing step to increase the accuracy of the further edge recognition output. The non-locals means (NL-means) and the median filters [13], [14] are used in this approach for image noise suppression. Combinations of both filters were found very effective in removing all unwanted image artefacts while keeping the tree-ring edges untouched. The algorithms implemented in the scikit-image Python library are suitable to achieve that.

Gradient computation: Once the volumetric imaging data are properly denoised, the next step consist in recognizing effectively the edge-boundaries of the tree-rings. As the tree-ring boundaries are characterized by a step intensity transition from late to early wood, this signal can be properly captured by the image gradient. For each X-CT slice, tree-ring edges are detected in the approach by applying the Sobel filter along *x* and *y* direction, yielding the image gradient. The gradient's output provides a thick edges map and the angles to the normal to the edges at each local point, which will be used as input data for subsequent steps. Sobel Filter implementations provided either in the scikit-image and OpenCV Python's libraries are suitable for this purpose.

Non-maximum suppression (NMS): To thin out the edges provided by the image's gradient; an NMS-algorithm was developed as described in [11]. The algorithm goes through all the points in the edge map and compares the gradients' magnitude of the point being processed with those of the two closets neighboring pixels along the ring structure direction, which is here taken as the direction having the largest gradient average magnitude. Then, the pixel with the highest intensity is kept and the others are set to zero, which results in very thin edges.

Final edge tracking: To assign the same intensity to the thin edges and to remove possible spurious responses (e.g., knots, resin ducts, etc.) from the NMS's output, double thresholding and connected components analysis (CCA) are performed [11]. The double thresholding procedure allows to classify all pixels into three classes: Strong (Intensity $\geq t_s$), weak ($t_i \leq$ Intensity $< t_s$) and non-relevant (Intensity $< t_i$), being the intensity of the latter set to zero. The high threshold value, t_s, is determined by using the Otsu's method [15] and the lower one is set to 0.5 t_s for each X-CT image. The CCA algorithm allows to classify strong pixels and weak pixel having a least one strong neighboring pixel as foreground. This results in a binary output image with fully connected edges as foreground (Fig. 2 (b)).

The whole procedure, including the developed NMS, double thresholding and CCA algorithms, has been implemented in Python 3.7 and the source code is available from the corresponding author upon request.

To conclude, it is worth underlining that although the proposed edge detector algorithm allows to calculate tree-ring boundaries slide-by-slide, the extracted tree-ring morphology is completely three dimensional, since the tree-ring surfaces coordinates are independent of the chosen reference system.

Novelty of the Approach

In contrast to previously proposed tree-ring edge detection procedures [6]-[10], the present approach provides:

1. a self-adaptive selection of the two thresholds values based on the specific image's properties.
2. automatic application of the edge-detector algorithm to a 3D image stack.
3. sequential combinations of the NL-means and median filters instead of a simple Gaussian filter, as it is used in the original version of the Canny algorithm. This enables to treat a wide range of wood samples having different anatomical structures, while keeping the key features of the tree-ring edges.

III. Results

The performance of the approach was tested on X-CT volumetric data from six wood species having different anatomical structures [16], namely, Douglas fir, Spruce fire, Larch, Hemlock, Cherry tree and Ash.

The tomographic experiment was conducted in a high resolution microfocus X-CT system (Diondo d_2, Germany). The measurements were conducted in high power mode of the X-ray source XWT-225 TCH+ from X ray works, Garbsen, Germany, with an operation voltage of 80 kV and a filament current of 300 uA. The radiographic projections were recorded with a 4343 DX- Id detector from Varex, Salt Lake City, U. S. A with a pixel size of 139 um. The distance between the X-ray source and the samples was 159 mm, whereas the distance between the source and the detector as set to 1100 mm, providing a magnification of 6.92 and nominal voxel size of 20 um. A total of 2400 projections were recorded which were converted into a tree dimensional image stack using the CERA reconstruction software from Siemens.

Fig. 2 shows the results of applying the proposed approach to the aforementioned wood species. For each sample, the measured tree dimensional X-CT image stack and its calculated three-dimensional tree-rings surfaces are shown. As it can be seen from the plots, the tree-ring detection approach performs very well for all wood samples examined. A putative reason for this excellent recognition is that for almost all cases, the tree-ring edges are well defined and fully connected. The key issues to achieve such high accurate result rely on

- providing properly denoised and edge enhanced input images to the edge detection algorithm, and
- using a self-adaptative selection of the two thresholds values based on the specific image's properties.

This is a substantial extension to the original Canny algorithm where a simple Gaussian filter is adopted and both thresholds are defined empirically, which may cause in some cases edges either fragmented or lost.

Filtering was the most time-consuming part of the procedure, taking around 15-30 min on a standard laptop computer (16 GB RAM, IntelCore i9 2.4GHz CPU), depending on the parameter setting. Nevertheless, the filtration has to be performed only once. Afterwards, edge recognition takes on average only a few minutes.

IV. Conclusions

An image processing approach was developed to extract 3D tree-rings automatically from X-ray computed tomography data. A key advantage of this algorithm is that it can extract the tree ring edges automatically with little to no user interaction. Therefore, it is optimally suited to analyze many samples as well as analyze CT image stacks. As the procedure provides 3D reorientations of the tree-ring edges it can be used for the inspection of anatomical features and in dendrochronology, to estimate tree-ring widths considering the whole shape of the tree-ring profiles. The latter enables to get a reproducible dating process independent of the operator's experience.

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