3D TRACKING OF CELLULOSE FIBRES IN VOLUME IMAGES

Maria Axelsson

Centre for Image Analysis
Swedish University of Agricultural Sciences
Box 337, SE-751 05 Uppsala, Sweden
maria@cb.uu.se

ABSTRACT

Segmentation of individual fibres in volume images is important when analysing the three dimensional (3D) fibre structure in paper and cellulose based composite materials. This paper presents a novel method for 3D tracking of individual fibres which can be used as a pre-segmentation step to a full cell wall segmentation or be used to estimate the fibre orientation. The tracking starts in one seed in each fibre and automatically extracts the local fibre orientation and the fibre centre point in each step using 3D information. Good results are obtained for cellulose fibres that are partially collapsed, cracked or irregularly shaped. The proposed method can also be used in other applications where tracking of tubular structures is of interest.

***Index Terms*—** 3D tracking, Image segmentation, Radon transform, Cellulose fibres, X-ray microtomography

1. INTRODUCTION

High resolution three dimensional (3D) volume images of paper and other cellulose based materials, such as fibre composites, have become available for 3D structure characterisation. This is due both to the advances in X-ray microtomography, which opens up the possibilities for non-destructive imaging of fibre networks [1] and due to other research efforts like [2, 3, 4]. The volume images are often large because of the high resolution needed to resolve fibre details and at the same time image a representative part of the material. This, together with the fact that the number of fibres per volume unit in the material is high, makes manual segmentation of the individual fibres feasible only for a small number of fibres. Automatic segmentation of the individual fibres in volume image data is therefore an important step in the characterisation of the 3D structure of fibre based materials. Individually segmented fibres give direct access to many important fibre properties such as connectivity, orientation, length and shape, and information about the fibre network. Such information is important for modelling properties of the fibre network like strength, optical properties and transport properties.

Cellulose fibres are long tubular structures with a void interior called a lumen. In paper and composite materials the fibre cross sections are very irregular. This reduces the possibility to use template based tracking methods. As can be seen in Figure 1 (left), the fibres are often cracked, partly collapsed or irregularly shaped. This is e.g. due to the fibre type or to mechanical stress during pulping. The fibres also have natural holes in the cell wall for fluid transport in the wood.

In a paper sheet the fibres are often aligned with the flow in the machine direction and each fibre has many connection areas with bonds to other fibres in the network. The structure is also very plane like.

Methods for tracking and segmentation of individual cellulose fibres has been presented by Aronsson [5, 6, 7], Holen and Hagen [8], Bache-Wiig and Henden [9], and Donoser and Bischof [10]. The first three methods are similar and use manual seeding and slice based techniques where each fibre is tracked using volume slices perpendicular to a fixed direction. The machine direction is often used. Only information from the closest slices are used and problems like cracks, holes and collapsed fibres must be handled separately. In [10] a method is presented where the fibre cross sections are identified as Maximally Stable Extremal Regions and tracked through the volume by connecting similar regions in a component tree. The fibres are also in this method tracked in a fixed direction.

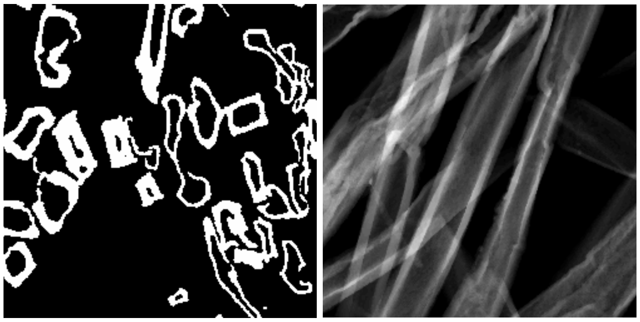

Fig. 1. (Left) Fibre cross sections in a binary volume image. (Right) A sum projection perpendicular to the fibre cross sections of a part of a binary volume image.

The fibre tracking method proposed in this paper is based on a model of the tubular structure of the fibres that builds on the fact that the fibre walls appear as lines with high intensity in sum projections of the fibre perpendicular to the fibre cross section. See Figure 1 (right) for an example of a part of a binary volume image that is sum projected perpendicular to the fibre cross sections.

The proposed tracking method implicitly handles the difficulties with cracked and partly collapsed fibres that must be treated separately in the slice based methods. Each fibre is tracked using a separate coordinate system that follows the local orientation of the fibre, which makes it possible to track a fibre in any direction and not only in a fixed direction as in the previous methods. 3D information in a neighbourhood around each point is used in each step of the tracking.

The tracking results in an approximation of the centreline of each fibre that can be used as input to a full cell wall segmentation or be used to estimate the fibre orientation. The method is demonstrated on binary volume data sets, but can be used directly on grey level data with good contrast. It can also be applied to tracking of other tubular structures in 3D, for example in medical applications.

2. METHOD

The 3D tracking method is outlined in the following steps:

1. Seeding of the fibres with one seed in each fibre. (Section 2.1)
2. The volume around the approximated fibre centre point $\mathbf{m}$ is described in a local coordinate system with $\mathbf{m}$ as origin and the approximated fibre direction $\mathbf{V}$ as one coordinate axis. (Section 2.2)
3. N images are created using sum projections perpendicular to the fibre cross section by rotations of the local coordinate system around the axis $\mathbf{V}$. (Section 2.3)
4. The N sum projections are radon transformed to identify lines corresponding to the fibre walls by locating local maxima. (Section 2.4)
5. New estimates of $\mathbf{m}$ and $\mathbf{V}$ are calculated from the identified lines and a step is taken in the $\mathbf{V}$ direction. The method is then repeated from step 2 above until the border of the volume is hit or not enough maxima corresponding to fibre walls are found. (Section 2.5)

2.1. Seeding

The first step in the fibre tracking method is selection of appropriate starting points in the input volume. This is done by manually marking the approximate centre point for each fibre in a slice that is relatively perpendicular to each fibre length axis. This gives the first estimates of the fibre cross sectional dimensions, the approximated fibre centre point $\mathbf{m}$ and the approximated fibre direction $\mathbf{V}$.

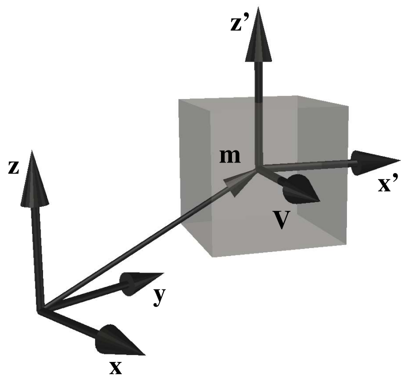

Fig. 2. The coordinate systems used in the tracking method.

2.2. Coordinates

The volume around the approximated fibre centre point $\mathbf{m}$ is described in a local coordinate system, $\mathbf{B}$, with the approximated fibre direction $\mathbf{V}$ as the first axis. The local coordinates are derived from the global coordinate system as, $\mathbf{x}' = \mathbf{z} \times \mathbf{V}$ and $\mathbf{z}' = \mathbf{V} \times \mathbf{x}'$, where $\mathbf{x}$, $\mathbf{y}$ and $\mathbf{z}$ are the coordinate axes in the global coordinate system that describes the input volume. The coordinate systems are illustrated in Figure 2. The grey box is the neighbourhood around $\mathbf{m}$ which is used as input data for two of the sum projections in the next step of the method. The image slice at the origin of $\mathbf{B}$ in the plane perpendicular to $\mathbf{V}$ is illustrated in Figure 3 (top left).

2.3. Projections

In each tracking step, N evenly distributed sum projections perpendicular to the fibre cross section are calculated in a neighbourhood of $\mathbf{m}$ by using rotations of the local coordinate system $\mathbf{B}$ around the axis $\mathbf{V}$. Four projections has been found suitable for cellulose fibres, but more projections could be added to get better estimates and to avoid problems with occlusion. In the case of four sum projections, two projections are calculated along the $\mathbf{x}'$ and the $\mathbf{z}'$ axes respectively and the two other projections are calculated along the same axes after $\mathbf{B}$ is rotated $\pi/4$ radians around $\mathbf{V}$. An example of a typical sum projection is shown in Figure 3 (top right).

Estimates of the fibre cross sectional dimensions from previous tracking steps are used to determine the size of the sum projected volume. In the projection direction the estimate from the perpendicular projection direction is used to limit the projection to the interval within the fibre walls. The estimate of the fibre dimension in the projection direction is used to ensure that both fibre walls are visible in the projected image. In the approximated fibre direction $\mathbf{V}$, a fixed number of slices are used. In this interval the projection of a fibre wall is assumed to have approximately constant orientation. Each sum projection is normalised with the maximum value in the image to be invariant to the size of the volume used for the sum projection.

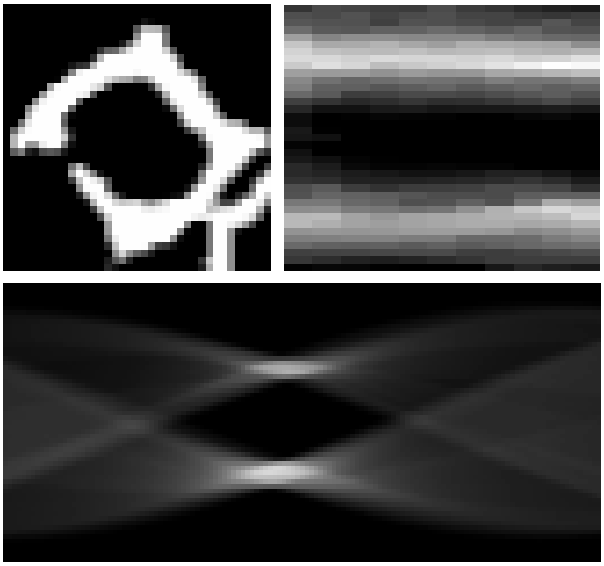

Fig. 3. (Top left) The image slice at the origin of $\mathbf{B}$ in the plane perpendicular to $\mathbf{V}$. (Top right) One of the sum projections perpendicular to the fibre cross section. (Bottom) The radon transform of the sum projection above.

2.4. Radon transform and maxima location

The radon transform is a well known transform that maps images using polar coordinates. Each output pixel is the sum of pixels along a ray through the input image with a given angle and radius. The origin of the polar coordinate system is located in the centre pixel of the input image.

The N sum projections are radon transformed to identify the fibre walls, that appears as lines with high intensity in the images, by locating local maxima. Before the transformation low values in the sum projections are set to zero. These values correspond to image details that cover only a small part of the volume in the projection direction. It is assumed that the fibre walls are found among the highest values in the transformed images. The radon transformed images are pixel wise normalised with the length of the projection ray for the given pixel for all ray lengths equal to or longer than the image size in the $\mathbf{V}$ direction. For shorter rays, the image size in the $\mathbf{V}$ direction is used for normalisation. An example of a radon transformed sum projection is shown in Figure 3 (bottom).

All local maxima in the radon transformed images are located and pairs of maxima, corresponding to the two fibre walls, are identified in each radon transformed image. The two maxima in each pair should be located at almost the same radon transform angle since they are assumed to be parallel. Some variation should be allowed in case the fibre dimensions increase or decrease. In addition, the new estimates of the fibre dimensions from the projection image should be close to the previous estimates. Since an estimate of the fibre centre point $\mathbf{m}$ is known that can be used to identify maxima in the top and bottom image half separately. Ideally a single maxima is found in each of the two halves. If a single maxima is found in one of the halves the correct maxima can be chosen among multiple maxima in the other half using estimates of the fibre cross sectional dimensions from the previous steps. Furthermore, an estimate of the fibre dimensions in a projection direction is only saved if two single maxima are identified in the corresponding radon transform.

2.5. Estimation of tracking parameters

The tracking continues if at least two images with maxima pairs can be found among the radon transformed images. The pairs with the strongest peaks are chosen for estimation of the new tracking parameters. The projection directions for the two images do not need to be perpendicular. From the two maxima pairs, the fibre dimensions, the projection of the fibre centre point and the mean fibre wall direction are calculated for the tracked fibre in the corresponding sum projections.

The position of $\mathbf{m}$ in the plane perpendicular to $\mathbf{V}$ is corrected by finding the intersection between two lines. Each line intersects the projection of the fibre centre point in the sum projected image and is oriented in the respective projection direction. A new estimate of $\mathbf{V}$ is calculated from the two mean fibre wall directions in the sum projections. For each sum projection image, a plane is spanned by the mean fibre wall direction, which is a vector in the sum projection image plane, and a vector in the projection direction. The new estimate of $\mathbf{V}$ is determined by the intersection between the two planes. A step from the corrected fibre centre point is taken in the new $\mathbf{V}$ direction. This generates the new estimate of $\mathbf{m}$ and the tracking steps are repeated from the calculation of a new basis $\mathbf{B}$ in Section 2.2. If the border of the volume is hit the tracking of the fibre stops.

3. EXPERIMENTS AND RESULTS

The performance of the fibre tracking method was evaluated on a set of volume images of cellulose fibre reinforced composite materials that was scanned at the European Synchrotron Radiation Facility (ESRF). The samples were imaged in absorption mode at beamline ID19 using synchrotron X-ray microtomography. The size of a volume element (voxel) is $0.7 \times 0.7 \times 0.7\ \mu\mathrm{m}$. Binary volume images with $1024 \times 1024 \times 256$ voxels were used in the test set.

Fibres in each volume was manually seeded and automatically tracked using the proposed method. In the tests, the step length was 2 and the number of slices used for the sum projections in the $\mathbf{V}$ direction was 10. In the sum projections all values below 0.5 was removed. The parameters used in the method are not sensitive and other similar values can be used with good results. The results show that both more tubular fibres and fibres with cracks, partial damages or partially collapsed fibres can be tracked using the proposed method. An

Fig. 4. A cellulose fibre that is tracked through approximately 800 volume slices. The white line is the approximated centreline. Note that the tracking passes the contraction of the fibre in the middle part without problem and handles the crossing fibres.

example of a tracking result is shown in Figure 4. This fibre was tracked through more than 800 volume slices. The white line is the approximated centreline, but estimates of the fibre cross sectional dimensions and the fibre orientation are also available for all tracked points.

4. DISCUSSION AND CONCLUSION

The proposed fibre tracking method has been shown to produce good results for fibres with cracks, irregular shape, holes or partial collapse. These problems are handled implicitly by using a tubular model of the fibre. The fibre can be tracked in any direction in the input volume using a separate coordinate system which follows the local fibre orientation and is updated in each step. The method is successful when tracking fibres with a shape which allows at least two sum projections of it to show two lines corresponding to the cell walls. The fibre model does not work in the case of completely collapsed fibres in binary images where the sum projection is a band and not two lines. In this case grey scale images or enhanced grey scale images could improve the results. Future work will include a more thorough evaluation of the tracking method and a full cell wall segmentation of the individual fibres. Depending on the application, an automated seeding step could be included as well. The method can also be applied to tracking of tubular structures in other types of volume data, like images of blood vessels.

5. ACKNOWLEDGEMENT

Data from the ESRF Long Term project ME-704 and support from The Paper and Fibre Research Institute in Trondheim are gratefully acknowledged. Support from Prof. Gunilla Borgefors, Dr. Stina Svensson and Dr. Joakim Lindblad at the Centre for Image Analysis is also gratefully acknowledged.

6. REFERENCES

[1] E.J. Samuelsen, Ø .W. Gregersen, P.-J. Houen, T. Helle, C. Raven, and A. Snigirev, "Three-Dimensional Imaging of Paper by Use of Synchroton X-Ray Microtomography," *J. Pulp Pap. Sci.*, vol. 27, no. 2, pp. 50–53, 2001.

[2] M. Aronsson, O. Henningsson, and Ö Sävborg, "Slice-based Digital Volume Assembly of a Small Paper Sample," *Nord. Pulp Pap. Res. J.*, vol. 17, no. 1, pp. 29–33, 2002.

[3] G. Chinga, P.O. Johnsen, and O. Diserud, "Controlled serial grinding for high-resolution three-dimensional reconstruction," *J. Microsc.*, vol. 214, no. 1, pp. 13–21, 2004.

[4] M. Wiltsche, *Three Dimensional Analysis of Paper Structure Using Automated Microtomy*, Ph.D. thesis, Graz University of Technology, 2005.

[5] M. Aronsson and G. Borgefors, "2D segmentation and labelling of clustered ring shaped objects," in *Proceedings of SCIA*, 2001, pp. 272–279.

[6] M. Aronsson and I.-M. Sintorn, "Ring Shaped Object Detector for Non-isotropic 2D Images using Optimized Distance Transform Weights," in *Proceedings of ICIP*, 2002, pp. 985–988.

[7] M. Aronsson, *On 3D Fibre Measurements of Digitized Paper - from Microscopy to Fibre Network*, Ph.D. thesis, Swedish University of Agricultural Sciences, 2002.

[8] R. Holen and M. Hagen, "Segmentation of absorption mode X-ray micro tomographic images of paper," M.S. thesis, Norwegian University of Science and Technology, 2004.

[9] J. Bache-Wiig and P-C. Henden, "Individual fiber segmentation of three-dimensional microtomograms of paper and fiber-reinforced composite materials," M.S. thesis, Norwegian University of Science and Technology, 2005.

[10] M. Donoser and H. Bischof, "Efficient Maximally Stable Extremal Region (MSER) Tracking," in *Proceedings of CVPR*, 2006, pp. 553–560.