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Estimation of fiber size
distribution in 3D X-ray μCT image datasets

Master’s Thesis in Intelligent Systems

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Acknowledgement

"The mediocre teacher tells. The good teacher explains. The superior teacher strives. The great teacher inspires."

We would like to say thanks to our parents whom gave us the opportunity to continue our studying in Master program, and we have to say our special thanks to our supervisors Dr Kenneth Nilsson, and Dr Cristofer Englund whom gave us any time for guiding and helping through this project and spent a lot of time through giving us information about this thesis.

Cover is a schematic picture of a press felt.
Details

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Abstract

The project is a thesis work in master program of Intelligent Systems that’s done by Alireza Mozaffari and Kunal Varaiya with supervising of Dr Kenneth Nilsson and Dr Cristofer Englund.

In this project we are estimating the depth distribution of different sizes of fibers in a press felt sample. Press felt is a product that is being used in paper industry. In order to evaluate the production process when press felts are made, it is necessary to be able to estimate the fiber sizes in product.

For this goal, we developed a program in Matlab to process X-ray images of a press felt, scanned by micro-CT scanner that is able to find the fibers of two different known sizes of fibers and estimates the depth distribution of the different fibers.

Keywords

Press felt, Eigenvectors, Eigenvalues, Tensor, Estimation fiber distribution
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1. Introduction

In daily life, we are using many fiber based materials. These materials are varying in many different shapes and variety, like wood fibers, carbon fibers, glass fibers, etc. The one of them that we are using each day is paper, like newspapers, magazines, books, sacks, bags, cleaning papers ….

There are different kinds of papers with different sizes and different qualities. In paper industry, the one of most important factors that can be affect the quality of paper is another fiber based material called Paper Machine Clothing (PMC).

Our thesis is presenting the estimation of depth distribution of fibers of different sizes in press felts.
1.1. Problem Formulation

The goal of this project is to use 3D image processing techniques to extract fibers with different sizes in a 3D image dataset. This project is initiated from a PMC producing company who has a solution that performs the fiber size depth distribution; however the computations are very time consuming with a low speed. Therefore, the company wants to have a faster program and confirm the results by another algorithm.

Here we first have a look at the problem, the goal, different ways of solutions, and giving an algorithm for the processing of a 3D image dataset to detect fiber structure. Our method is based on estimating the local 3D structure tensor and eigenvalue analysis. The dataset is computed by an X-ray micro computed tomography scanner.
2. Background

2.1. Paper manufacturing

This thesis is a project for Albany Company in Halmstad [1]. Albany is an international company that produces different textiles and coated products for paper industry. The main product’s name that our project is working with is press felt. This product is being used in paper industry for pressing water from paper sheet. The paper sheet is formed from pulp. Pulp is the main material of paper and consists of 99 percent water and one percent wood fibers. In production there are three main steps for draining water from the pulp and producing paper. In each step they use special kind of PMC.

Figure 1. Paper manufacturing [source: Albany]
Figure 1 shows the manufacturing process of paper. Figure 2 is the model of process of paper manufacturing. As we see in figure 2 there are 3 different steps, colored by green, blue and red.

Figure 2. Schematic illustration of paper manufacturing steps [source: Albany]

The first step, that is denoted by “A”, is the forming section. In this section the paper sheet is formed using forming fabric (figure 3). The water content is 99% in the beginning of the forming section and with approximately 80% the paper reaches the next section. The next step as it is denoted by “B” in the figure 2 is the pressing section (Figure 4). In this step a press felt that contains fibers and weaves is used to press the water out of the paper sheet. This PMC is produced at Albany international in Halmstad. At the end of this section the paper contains around 50 percent water. Then it goes to drying section as we see in figure 2 which is denoted by “C”. Here drying fabrics are used to transport the paper around heated cylinders to be dried. The more dried paper that comes to this section from the blue step, the more energy can be saved in the drying process. So it is important to get
as much drier paper in previous sections as we can. At the end of this section the final paper contains less than 5 percent water.

Figure 3. A slice of a Forming fabric [source: Albany]

Figure 4. Pressing section [source: Albany]
In figure 5 we see the press felt which is being used in press section and in figure 6 we can see the fabric that we use in drying section.

Figure 5. A slice of a press felt being used in the press section [source: Albany]

Figure 6. A slice of a dryer fabric being used in the drying section [source: Albany]
2.2. Press felt

The production of press felts is done in to 3 main steps. In the first step the based weave is produced in weaving looms.

In the second step the fibers are prepared by making them homogenized by putting them layer by layer to make web mass of fibers.

At the last step the fibers are needled in to the base weave and the press felt is created.

As we see in figure 7 the parts which are denoted by "F" are representing the fibers and the denoted parts by "W" are the base weaves.

The press felt can be of different types where each type has its own special use. The difference comes from choosing different sizes of fibers in the production process. Usually the products have fibers of two different sizes. A press felt can be up to 14 meters in width and is normally between 10 to 30 meters long. The thickness of a press felt is normally between 2 to 4 mm [2].

One side of the press felt is needled with fibers with small, and the other side is needled with large fiber diameter. The reason is that in the press section, where the paper sheet is pressed, we have the small fibers at the paper side to get a smooth paper surface. But on the other hand, at the side where the felt is getting touched by the roll in high pressure we need big sizes of fibers to have a good insurance against tear and wear and high drainage. So as the depth position of different fiber sizes are a big factor of quality of paper, it is so essential to know the depth distribution of different sizes of fibers in the product for the company. So the goal of this project is the estimation of different sizes of fibers in the press felt.
Figure 7. Schematic view of press felt
2.3. Related Works

The company is already using one program for estimating the depth distribution of fibers in the PMC (press felt) product. The program is using a local thickness algorithm. [3, 4]

2.3.1. Algorithms

There are different algorithms to detect a 3D object in a 3D image. The algorithm of the already used program is based on distance transform and uses local thickness algorithm [4]. For each point in the 3D volume this algorithm calculates the diameter of the largest sphere that fits inside the object and contains the point. Its base work for finding fibers is calculating the distances between fiber walls. It is a good algorithm for finding the objects that have plate, cube or cylinder shapes. The good point of this algorithm is that it does not depend on structural assumptions. It has been used for finding the thickness of bone structures, planning dental surgery...etc [4].

There are some algorithms for circle detection like the algorithm that is being used for detecting the spots in 2D Electrophoresis Gels by using symmetry features and basic signal processing. This method uses 2D Gaussian filter for smoothing and noise reduction of images. It also uses second derivative to get information about local surface [5]. One algorithm for circle detection is using Hough transform to detect low contrast circular objects with a given radius r. If the r is unknown the algorithm has to be run for probable radiiuses [6]. Other algorithm is fast circle detection using gradient pair vectors that the main idea is gotten from edge oriented methods and finding the circular objects that are darker or brighter than their background in the image [7]. The other algorithm for finding fibers is 3D structure tensor presented by Maria Axelsson [8].
3. Method

Our method is inspired from Maria’s algorithm [8]. The difference is the filters that we use to construct the structure tensor $S$, in equation 7.

Our method of finding a fiber structure in a local neighborhood is correlated with the least variation of the eigenvector that are parallel to the fiber direction. We use the partial derivatives of a 3D Gaussian filter to compute the 3D gradient $\Delta f = \begin{bmatrix} \partial_x f & \partial_y f & \partial_z f \end{bmatrix}$ (equation 1).

Each element of the gradient is calculated by:

$$
\partial_x f = ((f \ast gz) \ast gy) \ast dx \\
\partial_y f = ((f \ast gz) \ast gx) \ast dy \\
\partial_z f = ((f \ast gy) \ast gx) \ast dz
$$

We compute the partial derivative by use of a 3D Gaussian filter (equation 2).

$$
G(x, y, z) = e^{\frac{-x^2}{2\sigma_x^2}} \cdot e^{\frac{-y^2}{2\sigma_y^2}} \cdot e^{\frac{-z^2}{2\sigma_z^2}} = G(x) \cdot G(y) \cdot G(z)
$$

Where:

$$
\frac{\partial}{\partial x} (G(x, y, z)) = \frac{\partial}{\partial x} \left( e^{\frac{-x^2}{2\sigma_x^2}} \right) \cdot e^{\frac{-y^2}{2\sigma_y^2}} \cdot e^{\frac{-z^2}{2\sigma_z^2}} = G'(x)G(y)G(z) = dx \ast gy \ast gz
$$
\[
\frac{\partial}{\partial y} (G(x, y, z)) = G'(y)G(x)G(z) = dy \ast gx \ast gz \tag{4}
\]

\[
\frac{\partial}{\partial z} (G(x, y, z)) = G'(z)G(y)G(x) = dz \ast gy \ast gx \tag{5}
\]

So \(gx, gy, gz\) are the smoothing filters and \(dx, dy, dz\) are the derivative filters, one for each direction \(x, y\) and \(z\). The width of the filters are tuned by changing the sigma-value \(\sigma = \sigma_1\) in equation \(2\).

The matrix \(T\) is computed as the outer product of \(\Delta f\). T matrix is calculating by the gradient value of each pixel (equation \(6\)).

\[
T = (\nabla f)^T (\nabla f) = \begin{bmatrix} \frac{\partial}{\partial x} f & \frac{\partial}{\partial y} f & \frac{\partial}{\partial z} f \end{bmatrix} \begin{bmatrix} \frac{\partial}{\partial x} f & \frac{\partial}{\partial y} f & \frac{\partial}{\partial z} f \\ \frac{\partial}{\partial y} f & \frac{\partial}{\partial y} f & \frac{\partial}{\partial y} f \\ \frac{\partial}{\partial z} f & \frac{\partial}{\partial z} f & \frac{\partial}{\partial z} f \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} f \frac{\partial}{\partial x} f & \frac{\partial}{\partial y} f \frac{\partial}{\partial y} f & \frac{\partial}{\partial z} f \frac{\partial}{\partial z} f \\ \frac{\partial}{\partial y} f \frac{\partial}{\partial x} f & \frac{\partial}{\partial y} f \frac{\partial}{\partial y} f & \frac{\partial}{\partial y} f \frac{\partial}{\partial z} f \\ \frac{\partial}{\partial z} f \frac{\partial}{\partial x} f & \frac{\partial}{\partial z} f \frac{\partial}{\partial y} f & \frac{\partial}{\partial z} f \frac{\partial}{\partial z} f \end{bmatrix} \tag{6}
\]

Then we estimate the structure tensor \(S\) for each 3D neighborhood \([9]\). We calculate the structure tensor by smoothing locally the tensor \(T\) by a 3D Gaussian filter with a sigma-value \(\sigma = \sigma_2\). Thus we have a structure tensor \((S)\) in each 3D point (equation \(7\)).

\[
S = \begin{bmatrix} \langle \frac{\partial}{\partial x} f \frac{\partial}{\partial x} f \rangle & \langle \frac{\partial}{\partial y} f \frac{\partial}{\partial y} f \rangle & \langle \frac{\partial}{\partial z} f \frac{\partial}{\partial z} f \rangle \\ \langle \frac{\partial}{\partial y} f \frac{\partial}{\partial x} f \rangle & \langle \frac{\partial}{\partial y} f \frac{\partial}{\partial y} f \rangle & \langle \frac{\partial}{\partial z} f \frac{\partial}{\partial z} f \rangle \\ \langle \frac{\partial}{\partial z} f \frac{\partial}{\partial x} f \rangle & \langle \frac{\partial}{\partial z} f \frac{\partial}{\partial y} f \rangle & \langle \frac{\partial}{\partial z} f \frac{\partial}{\partial z} f \rangle \end{bmatrix} \tag{7}
\]

We have to Tune the sigma values \(\sigma_1\) and \(\sigma_2\) of the filters so they would be sensitive to the size of the structure to be detected.
In the next step we compute the eigenvalues and eigenvectors of structure tensor (S) to estimate the local structure anisotropy. By sorting the eigenvalues in a descending order as \( \lambda_1 \geq \lambda_2 \geq \lambda_3 \) we are calculating a certainty measurement for finding the fibers. Our certainty value that we show as \( C \) is being calculated by this formula:

\[
C = \frac{(\text{eigenvals}(2) - \text{eigenvals}(3))}{\text{eigenvals}(1)}
\]  

(8)

This \( C \) value is between zero and one. When \( C \) is large enough (close to 1) it means that there is no signal variation in the direction of eigenvector \( e_3 \) that is parallel to the direction of fiber. In other word the signal variation is more in directions of \( e_2 \) and \( e_1 \) than \( e_3 \). So there is a high probability to have fiber there. So we can say in that point we should have a fiber.

We have experienced some different ways of post processing on dataset after getting certainty values of each image to recognize the small diameter and large diameter fibers separately. Our experiment is described in experiment section 4.

Among the methods that we tried, we have chosen following order method to get final result:

First: Computing certainty values of each image in data set in the way that we described in this section.

Second: Smoothing the certainty value images (described in 4.4.3. Smoothing before multiplication and inhibition)

Third: Multiplication of original image with the certainty images (described in 4.4.1. Noise reduction)

Fourth: comparison the results of the multiplication part for small and big sizes and dedicating zero value to the pixel that has the smaller value in the comparison, since the highest value remains (described in 4.4.2. Inhibition)
4. Experiments

4.1. Dataset

Previously the internal part of a press felt was examined by cutting and imaging using a microscope. But this technique could cause the movement of the fiber positions in the press felt. Nowadays we can analyze the internal structure of the press felt that we receive from X-ray micro tomography scanner (figure 8).

Figure 8. Desktop X-ray micro tomography scanner (Sky scan 1172)
The dataset is a stack of high resolution 2D images of the press felt. The scanner computes 2D images of the 3D press felt sample. So we have a stack of 2D images of the object and a 3D view of it. The maximum resolution is 1 µm per voxel. Maximum size of the sample for the scanner is 68 mm in height and 35 mm in two other dimensions. In figure 9 we see some examples of images from press felt at different depth. The dataset that we work with consisted of 291 of such images which each image is 200 pixels in each x and y axes.

Figure 9. Scanned images of PMC with X-ray tomography scanner
In the scanner there is an X-ray source that is penetrating X-rays into the samples while the sample is rotating with small degree between each rotation. Meanwhile the camera on the other side is capturing images. (Figure 10)

Figure 10. Scanner structure (image is from Albany)
4.2. First Experiment

For extracting the fiber we tried different values of $\sigma_1$ (derivative filters) and $\sigma_2$ (smoothing filters) to have the best result. We want to have high certainty values of fibers in result images. So we tried to find a lower boundary (a threshold value) of certainty values where in that range, we have the most probability of having fibers. We mentioned the boundary: $T$ and we started to give different values to $T$ and threshold certainty values in the way that the certainty values which are greater than that $T$ are presenting the fibers. By comparing the results of threshold images with the original image by visual inspection we have found a good $T$ boundary value. In figure 11 we can see a good result that the fibers are well appeared with the $T$ value of 0.45. In the result that we see in figure 11 (right image), we see the threshold certainty values which are greater than 0.45.

![Figure 11. Left: Original picture. Middle: Certainty image (C values of each Pixel). Right: Threshold certainty image. (High C values)](image)

As we see in figure 11, we have a good sigma values to extract the fibers.
4.3. Tuning the algorithm

The main problem is to distinguish between fibers with large and small diameter fibers. Therefore, we should have specific sigma values for smoothing ($\sigma_2$) and derivative filters ($\sigma_1$) to be sensitive to special fiber sizes. In figure 12 we can see two different results, one for fibers with large diameter and the other for fibers with small diameter. Among all sigma values for filters we have chosen the ones which gave better result in separating the two fiber sizes. This choice of special sigma values is done by comparing the results of different sigma values by visual inspection.

![Image](image.png)

Figure 12. Left is original image, and top right is certainty image for fibers with small diameter, bottom right is certainty image for fibers with large diameter.
4.4. Post processing

4.4.1. Noise reduction

For getting better result it is good to suppress noise, the way we use here is multiplication of original image with the certainty images. We use this method instead of thresholding the certainty images that was described earlier in section 4.2. In figure 13 we can see the result for fibers with small diameter and in figure 14 for fibers with large diameter.

Figure 13: Above: original image and right, the certainty image for fibers with small diameter, Below: The multiplication of them.
Figure 14. Above: the original image and the certainty image for fibers with large diameter,

Below: The multiplication of two above.
4.4.2. Inhibition

For an assurance to have a specific fiber size in each pixel, we compare the results of the multiplication part for small and big sizes. We give zero value to the pixel that has the smaller value in the comparison and the highest value remains (Figure 15).

![Image of multiplication result for small and big fibers.](image1)

![Image of result after inhibition for small and big fibers.](image2)

Figure 15. Above left: is the image of multiplication result of small fibers and to the right for big fibers. Down is the result after the inhibition, left for small and right for big fibers.
4.4.3. Smoothing before multiplication and inhibition

In some results from some datasets after post processing, for both big and small fibers, we see the white pixels which present the fiber, are not smooth. Therefore, before applying multiplication and separation, we apply 3D low pass filtering on the certainty images. After that we do the multiplication separation (inhibition) procedure. We can see in figure 16 how better the result by this way is.

For the 3D smoothing the sigma-value is found by experiment.
Figure 16. Above: The certainty images result without extra low pass filtering. Middle: Result of multiplication and inhibition part without low pass filtering of certainty images. Below: Result of multiplication and inhibition of low pass filtered certainty images.
4.5. Depth distribution of fibers

We present the depth distribution of fiber sizes in the fabric as a graph which x-index is the depth of the fabric and the y-index is the amount of fiber in that special depth (figure 20). For each image in the dataset, we sum the post processed certainty values in row and columns to have the whole quantity of fibers in each image, then we present the normalize value of it for each image in dataset. The normalization is done by dividing the assumption of certainty values of each image by the assumption value of certainty values of the image that has the most amount value of assumption of certainty values. So for each image we get the value between zero and one and the image in dataset which has the most certainty value gets the value of one. We do it separately for small and large fibers and we show it in a bar diagram. The certainty images of the data set are more valid after some first images that the filter is totally inside the 3D-image. So in graph we can skip the result of the first certainty images and consider the 25th image as the beginning of the dataset. In figure 17 we see the image and the final result of our algorithm after getting certainty values, multiplication and inhabitation in 25th image in dataset and in figure 18 and 19 we see the distribution of fibers in middle and end of dataset respectively. The result graph can be compared to the graph which is come from another algorithm that Albany uses (figure 21).
Figure 17. 25\textsuperscript{th} image in dataset (Beginning of the data set). Left: Original image. Middle: Fibers with small diameter. Right: Fibers with large diameter.

Figure 18. 125\textsuperscript{th} image in dataset (middle of the data set). Left: Original image. Middle: Fibers with small diameter. Right: Fibers with large diameter.

Figure 19. 225\textsuperscript{th} image in dataset (end of the data set). Left: Original image. Middle: Fibers with small diameter. Right: Fibers with large diameter.
Figure 20. Left: Fibers with small diameter. Right: Fibers with large diameter, x index is depth and y index is amount of fiber.

Figure 21. Result graph from Albany, Above: result of large diameter fibers, Below: result of small diameter fibers. X index is depth and y index is amount of fiber.

Some other results are shown in appendix part.
5. Discussion and future work

The algorithm that we used can be compared with the algorithm that Albany uses in speed of computation. With a normal computer with a normal speed, our algorithm takes time about 100 minutes for computing on a dataset of 100 images. So it is about 60 second for computing on each image. In addition now we have the presentation of distribution of fibers in depth of press felt which is shown in graph (figure 20) that can be compared with the graph result by the other algorithm (figure21), which was our main goal. As we see the similarity in both graphs with same peaks in almost same area.

There are some points to be continued as future work to improve and complete the plan. One can be making the algorithm more user-friendly, for the people who are not familiar with Matlab. The other can be using other kinds of filters to make structure tensor and see which is better.

The other work can be tracking the color in images of dataset by coloring the fibers in press felt.

Here we used the algorithm to find the distribution of different size of fibers in press felt.

The algorithm can be discussed to be used to find other 3D subjects in other datasets from other materials.
6. Summary and Conclusion

The project is done by master students (Alireza Mozaffari & Kunal Varaiya) in Intelligent Systems.

The project is done in Matlab which is estimating the distribution of different sizes of fibers in press felt; press felt is a material which is being used in paper industry to dry the paper sheet. The done project now can be used to evaluate the production process of press felt to see if it has the standard qualities.

We can easily see the similarity between the results by a comparison of the results of our project that are shown as graphs, which are showing separately the distribution of fibers for large and small diameters, with the graph results of Albany for large and small diameter fibers.

As we see in the graphs for the large diameter fibers, from our project and Albany program, they both have peaks and falls in same areas. This similarity is also obvious in the graphs for small diameter fibers.

By this similarity we can confirm the results of Albany about distribution of fibers with different sizes and have an assurance of our knowledge about the distribution of fibers with different diameters in pressfelt.
Bibliography

[1] www.albint.com


Appendix

Here, some results and the correlated graphs are shown. The results are by different sigma values after post processing for fibers with small diameters and fibers with large diameters.

Figure 22. Above: original image (left), fiber with small diameter (middle) by $\sigma_1=1.1$ and $\sigma_2=1.3$, fiber with large diameter (right) by $\sigma_1=1.8$ and $\sigma_2=1.9$. Below: depth distribution of fibers with small diameter (left), depth distribution for fibers with large diameter (right)
Figure 23. Above, original image (left), fiber with small diameter (middle) by $\sigma_1 = 1.1$ and $\sigma_2 = 1.3$, fiber with large diameter (right) by $\sigma_1 = 2.0$ and $\sigma_2 = 3.2$; Below: depth distribution of fibers with small diameter (left), depth distribution for fibers with large diameter (right)
Figure 24. Above, original image (left), fiber with small diameter (middle) by $\sigma_1 = 1.2$ and $\sigma_2 = 1.3$, fiber with large diameter (right) by $\sigma_1 = 2.0$ and $\sigma_2 = 2.3$; Below: depth distribution of fibers with small diameter (left), depth distribution for fibers with large diameter (right).
Figure 25. Above, original image (left), fiber with small diameter (middle) by $\sigma_1 = 1.2$ and $\sigma_2 = 1.4$, fiber with large diameter (right) by $\sigma_1 = 2.2$ and $\sigma_2 = 2.4$; Below: depth distribution of fibers with small diameter (left), depth distribution for fibers with large diameter (right)
Figure 26. Above, original image (left), fiber with small diameter (middle) by $\sigma_1 = 1.2$ and $\sigma_2 = 2.4$, fiber with large diameter (right) by $\sigma_1 = 2.0$ and $\sigma_2 = 2.4$; Below: depth distribution of fibers with small diameter (left), depth distribution for fibers with large diameter (right).
Figure 27. Above, original image (left), fiber with small diameter (middle) by $\sigma_1=1.2$ and $\sigma_2=1.4$, fiber with large diameter (right) by $\sigma_1=2.2$ and $\sigma_2=2.4$; Below: depth distribution of fibers with small diameter (left), depth distribution for fibers with large diameter (right)
Figure 28. Above, original image (left), fiber with small diameter (middle) by $\sigma_1 = 1.2$ and $\sigma_2 = 3.2$, fiber with large diameter (right) by $\sigma_1 = 2.0$ and $\sigma_2 = 3.2$; Below: depth distribution of fibers with small diameter (left), depth distribution for fibers with large diameter (right)