Fiber diameter measuring method of textile materials based on phase information

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Abstract. For achieving rapid and accurate measurement of fiber diameter, so as to evaluate product performance and guide the improvement of manufacturing process, a method based on phase information for measuring fiber diameter of which the fiber images of textile materials is collected by scanning electron microscope was proposed. Firstly, the improved Kuwahara filter is used to smooth the fiber image and enhance the foreground target. Then the fiber edge was detected by phase consistency method and repaired. Then, the spatial position and direction information of each pixel on the axis of a single fiber were determined, and the boundary pixel points were found by scanning along the vertical direction of the axis. Finally, the fiber diameter is calculated according to the position of border pixel points obtained by scanning. The experimental results show that this method can accurately and effectively measure the fiber diameter. Compared with the standard manual measurement, the fiber with a relative error of less than 2% accounts for 95% of the total fiber.

1. Introduction
Modern textile technology is a new technique for multi-scale processing of the structure of fiber or fiber aggregation. In order to produce textiles that satisfy clothing, decorative and industrial needs, it's important to get information about textile fibers. Fiber diameter equal to the linear density of textile material is an important geometric parameter of the fiber. The size of the fiber diameter has a great influence not only on fiber strength, elongation, stiffness, elasticity, but also on the handle of textile, style and the processing of yarn and textile. The smaller fiber diameter can get greater friction of the fiber body and higher yarn forming strength. The contact area between the fibers in the yarn forming section is large and the probability of slipping is low, so the yarn strength is improved [1][2][3]. In addition, in the international trade of textiles, both the seller and the buyer specifies the diameter of the fiber.

At present, there are mainly two methods for measuring fiber diameter. The first method is based on whole fiber image processing, and the second method is collecting a single fiber image for processing. The basic idea of both methods is: firstly, pre-process the image, enhance the image contrast and filter out the noise; then conduct edge detection, refinement and line segment connection; finally measure the diameter according to the repair fiber edge line [4][5][6]. But the current approach doesn't mention the overlap of the fibers or the bonding of the fibers. It's difficult to get a single fiber, because the fibers are dense and adhesions overlap.
In the above methods, the poor measurement effect of fiber diameter is due to the low accuracy of identifying a single fiber. How to accurately identify a single fiber, and how to measure as much fiber as possible in a fiber image is the key point to our current research.

In this paper, a method for measuring fiber diameter of textile materials based on phase information is proposed, which is based on the fiber images with magnification of 20000 collected under scanning electron microscope. Phase consistency is used to extract the edge of the fiber image and identify the single fiber. Then, scan along the direction perpendicular to the central axis to find the edge pixel points, so as to obtain the pixel-level width of the fiber.

2. Fiber diameter measurement based on phase information

2.1 Preprocessing

2.1.1 Improved Kuwahara filtering

For the problem that Kuwahara filter is prone to block effect, the shape of sub-blocks can be changed and the local mean can be replaced by local weighted value [7]. Here, an adjacent region around the pixel point is evenly divided into 8 fan-shaped regions, and the improved Kuwahara filter is used to filter the fiber image [8]. Images before and after filtering is shown in Fig. 1:

![Images before and after filtering](image.png)

Fig. 1 Comparison before and after filtering. (a) Fiber image before filtering; (b) Fiber diagram after filtering; (c) Local area of fiber image before filtering (d) Local area of fiber image after filtering

2.1.2 Foreground target enhancement

In the process of image acquisition, some fibers in the collected fiber images are blurred due to different focuses. In order to highlight the foreground target with clear edges, this paper adopts mathematical morphology to enhance the foreground target. Add the filtered image to the result after the high hat transformation, and subtract the result after the low hat transformation to obtain the enhanced result:

\[ E(f) = f + T(f) - B(f) \]

Here, \( f \) is the target image to be operated, \( T(f) \) is the output image after high hat transformation, and \( B(f) \) is the output image after low hat processing.

After the high-low hat method, the output fiber image is clearer, the foreground target is prominent, and the single fiber is enhanced, as shown in Fig. 2.
Fig. 2. Image after high and low hat transformation. (a) Fiber image before transformation; (b) Output image after transformation of high and low hat.

2.2 Edge detection and repair

In order to ensure the accuracy of fiber diameter measurement, the primary task is to accurately locate the fiber edge. On the basis of fully analyzing the characteristics of fiber image, an edge detection algorithm based on phase consistency is introduced in this paper.

2.2.1 Edge detection and refinement based on phase consistency

In edge detection methods, the algorithm based on gray scale and linear filtering is widely used, like the typical Canny and Log operator. But the gradient threshold of these algorithms is difficult to set, especially when gray level difference between the target object and the background is very small, the edge features are difficult to be detected.

Morrone and Owens defined the phases consistency function [9]:

$$\Phi(p, \omega) = \max_{\phi(x) \in [0, 2\pi]} \frac{\sum_{n} A_n(x) \cos(\phi_n(x) - \phi(x))}{\sum_{n} A_n(x)}$$

Here, $A_n(x)$ is the amplitude of the nth Fourier component at the point x, and $\phi_n(x)$ is the phase of the nth Fourier component at the point x, so that the maximum $\Phi(p, \omega)$ is the average local phase weighted by the amplitude of all Fourier components at the point. Therefore, the point with the maximum phase consistency corresponds to the point with the minimum weighted average transformation of the local phase.

When the 1D signal is extended to 2D image, firstly, the polarizable filter is convoluted with the extension function in the vertical direction, and then convoluted with the filter bank in the horizontal direction. The polarizable filter function is:

$$F(\omega, \theta) = G(\theta) \ast H(\omega)$$

Here, $G(\theta)$ is the expansion function, constitutes the angular filter; $H(\omega)$ is the filter bank, $\theta$ is the direction Angle, $\omega$ and is the angular frequency.

In this paper, the following formula is selected to construct angular filter:

$$G(\theta) = \frac{\cos(\Delta \theta) + 1}{2}$$

Here, $\Delta \theta$ is the difference between the directional angle of the angular filter and the pixel angle.

Radial filtering uses Log Gabor wavelet to reflect and process the frequency response of natural image more realistically. It can extract more local frequency information, which is conducive to the calculation of phase consistency. In this paper, the following formula is selected to construct the radial filter:

$$H(\omega) = \exp\left(-\frac{(\ln(\omega / \omega_0))^2}{2(\ln(\beta / \omega_0))^2}\right) \cdot \frac{1}{\sqrt{1 + \varepsilon_2^2 T_\nu(\omega / \omega_0)}}$$

Here, $\omega_0$ is the central frequency of the filter; $T_\nu(\omega / \omega_0)$ is an order N Chebyshev polynomial; $\varepsilon_2$ is the ripple parameter, and $0 < \varepsilon_2 < 1$. 
On the basis of the above analysis, the method steps for edge detection of fiber image with phase information are as follows:

1. Fourier transform is performed on the acquired fiber image.
2. Use the above $G(\theta)$ calculation formula to construct the angular filter, and use the filter to filter the fiber image Fourier coefficient in $q$ directions.
3. Use the above $H(\omega)$ calculation formula to construct a radial filter, and then the fiber image processed by the angular filter on $s$ different scales respectively.
4. Calculate the sum of the local energy and the amplitude of the Fourier component for each point superimposed on multi-scale multiple directions.
5. Finally, the phase consistency matrix of fiber image can be obtained by using the results of angular filter and radial filter, and the matrix can be converted into gray image as the output result, as shown in Fig. 3.(a).

The phase consistency gray scale generally reflects the edge profile of the fibers in the fiber image, but it can be found that the fiber edge line width is generally not a single pixel. As there is noise in the image, and the fibers are crossed and overlapped with each other, there will be fiber adhesion in some areas, which will lead to some false edges and broken edges in the edge detection of the fiber image, so this does not achieve the ultimate goal of image edge detection. For this reason, this paper adopts the non-maximum suppression method based on the bilinear interpolation and the adaptive double-threshold method to obtain the two-valued edge graph of a single pixel, as shown in Fig. 3 (b).

![Fig. 3 Edge detection. (a) Edge detected by phase consistency; (b) Fiber edge detection results obtained by this method](image)

### 2.2.2 Edge repair

Due to the influence of light, some weak edges may be missed in edge detection, and some burrs and short lines may exist after refinement, resulting in fracture and incomplete edge lines. These conditions have a great impact on the identification of a single fiber, and the refined fiber edge image must be repaired and corrected to obtain a relatively complete fiber edge, providing a reliable basis for future measurement [10]. Therefore, in order to obtain a complete fiber edge, it is necessary to take a series of operations to repair and correct the fiber edge, and repair the original incomplete fiber edge segment into a complete fiber edge. Common edge repair includes intersection point removal, burr removal, short line removal and short edge repair.

After edge repair, the fiber edge line is clearer and not confused, as shown in Fig. 4.

![Fig. 4 Edge repair results](image)
Fig. 4 Fiber edge reparation. (a) Fiber edge image after reparation; (b) Local image before reparation; (c) Local image after reparation

2.3 Diameter measurement

2.3.1 Fiber identification
After a series of treatment and repair of the fiber edge, the edge of each fiber is composed of two single-pixel wide lines. The main work of this section is matching all edge lines in the repaired edge image, and the two edges successfully matched are considered as belong to the same fiber, so as to complete the identification of a single fiber. After edge repair, the X and Y coordinates of each point of the fiber edge curve are recorded in an array. The coordinates of each point in the array are fitted by the principle of least square method, and constraints are established to determine whether the two line segments are matched [11][12]. If constraints are satisfied at the same time, the two edges are considered to be matched successfully. Fig. 5 shows the fiber identification and filling result.

Fig. 5 Fiber recognition images. (a) Fiber edge matching results; (b) Fiber recognition results

2.3.2 Fiber diameter measurement
According to the fiber identification results, the fiber central axis is obtained. By using the spatial position and direction information of pixels on the central axis, the edge boundary pixels on both sides of the current point are scanned in the vertical direction of the central axis, so as to obtain the pixel-level width of the fiber.

The specific steps are as follows:
(1) Firstly, the identified single fiber filling area (as shown in Fig. 5(b)) was expanded, so as to ensure that the real fiber edge falls in the filling area;
(2) Calculate the center line of the filled area according to the coordinates of the four vertices of the filled area, and get the central axis of the fiber;
(3) Based on the edge detection results in Fig. 4(a), scan the edge line with the center line obtained in step (2), as shown in Fig. 6;
(4) Calculate the central axis and axis Angle $\theta$ according to the Bresenham algorithm. Choose five points in the central axis as a starting point for scanning in the perpendicular direction. (as shown in Fig. 7) $P_i$ is on the central axis and the dotted line is edge of fiber, scan with 1 pixel along a direction perpendicular to the fiber, then find edges on both sides of the boundary coordinates $Q_1$, $Q_2$;
(5) The Euclidean distance of $Q_1$, $Q_2$ is the fiber pixel diameter.
In this paper, 5 points were taken as the starting point of scanning at the interval of each central axis, and 5 fiber diameter measurements were obtained through scanning calculation. Mean values of these 5 measurements were taken as the final diameter measurements of the current fiber. Finally, the actual width of the fiber can be obtained by proportional conversion according to the ruler set in fiber collection.

3. Experimental results and analysis

This paper presents an algorithm for measuring fiber diameter based on phase information. By using this algorithm to process fiber image, a large number of fiber diameter data can be obtained. In order to evaluate the accuracy of fiber diameter data, the measured data were taken as the standard data and compared with the results of this paper.

Traditional ultra-fine fiber diameter measurement is completed by manual measurement of images collected by electron microscopy. In this paper, the manual measurement software image-j is used for manual measurement of fiber images. Then, the accuracy and stability of the measurement data are evaluated. Because the distribution of fibers in textile materials is very complex and special, there is no unified method to determine the diameter of fibers. There is a certain subjectivity in the actual operation process, but it can make up for the deficiency by averaging multiple measurements. The algorithm is evaluated by using the average diameter of multiple measurements as the standard data. In this paper, the mean value of 5 measurements was taken as the standard data of fiber diameter.

3.1 Accuracy analysis

In this experiment, 74 fiber diameters photographed at different magnification ratios under scanning electron microscopy were measured. Part of the measurement results of the method in this paper are shown in Table 1, and the experimental errors were analyzed through two parameters, namely the absolute error between the measured values of the algorithm in this paper and the mean values of the manual measurements \( \sigma_1 \), and the relative error between the measured values of the algorithm in this paper and the mean values of the manual measurements \( \sigma_2 \). Expressed as:

\[
\sigma_1 = |i - \bar{l}_m|
\]

\[
\sigma_2 = \frac{\sigma_1}{\bar{l}_m}
\]

Here, \( i \) is the algorithm measurement result of each diameter, and \( \bar{l}_m \) is the average value of manual measurement of each diameter. The experimental results show that 77% of the fibers with a relative error of <1% and 95% of the fibers with a relative error of <2% account for the total fiber. The measurement results are relatively accurate.
Table 1 Partial fiber diameter measurement results

| NO. | Manual Measurement/nm | This Method | Absolute Error | Relative Error |
|-----|-----------------------|-------------|----------------|----------------|
|     | 1                     | 2           | 3              | 4              | 5              | Average Value | /nm | /nm | /%   |
| 1   | 829.28                | 824.77      | 823.60         | 817.57         | 823.78         | 824.77        | 0.99 | 0.12 |
| 2   | 523.51                | 524.50      | 531.62         | 516.31         | 524.59         | 524.49        | 0.11 | 0.02 |
| 3   | 741.62                | 747.93      | 739.73         | 729.73         | 739.82         | 747.28        | 7.46 | 1.01 |
| 4   | 519.64                | 516.40      | 519.82         | 524.59         | 519.91         | 520.77        | 0.86 | 0.17 |
| 5   | 771.62                | 769.91      | 769.73         | 765.50         | 769.55         | 766.85        | 2.70 | 0.25 |
| 6   | 645.59                | 645.50      | 646.40         | 644.95         | 647.30         | 645.95        | 641.50 | 4.45 | 0.19 |
| 7   | 1024.2                | 1024.5      | 1023.78        | 1022.34        | 1020.45        | 1023.06       | 1022.91 | 0.15 | 0.01 |
| 8   | 754.41                | 752.79      | 755.32         | 756.31         | 755.50         | 754.86        | 749.90 | 4.96 | 0.16 |

3.2 Fiber diameter uniformity analysis
The uniformity of fiber diameter has an important effect on fiber material. After measuring the fiber diameter, this section calculates the variance of the fiber diameter in the figure by taking two fiber pictures as examples. The small variance indicates that the fiber thickness is relatively uniform.

![Fig. 8 Fiber diameter identification results (1)](image1)

![Fig. 9 Fiber diameter identification results (2)](image2)

After calculation, the pixel-level variance of fiber diameter in the image shown in Fig. 8 is 123, and the pixel-level variance of fiber diameter in the image shown in Fig. 9 is 98, indicating that the fiber diameter distribution in Fig. 9 is relatively uniform.

4. Summary
A method for measuring fiber diameter of textile materials based on phase information is proposed. Firstly, the improved Kuwahara filter was used to filter the fiber image and enhance the foreground target. Then, the method based on phase consistency was used to detect the fiber edge and repair the edge, including deleting the intersection point, short line and burring, and carrying out edge fracture connection. On this basis, the spatial position and direction information of each pixel on the central axis of the single fiber was identified.
Further research can be carried out in the following aspects in the future.

Firstly, due to the limited conditions for image collection, this paper only measures the fiber image magnified 20,000 times. However, there are still many types of actual fiber images. In the future, more and more complete fiber images need to be collected for measurement.

Secondly, the recognition rate of single fiber in the algorithm of measuring fiber diameter in this paper needs to be improved. In the future work, deep learning technology can be used to segment single fiber to improve the recognition rate of single fiber and further comprehensively measure fiber diameter.

Thirdly, this paper mainly measures the diameter of the fiber with a straight shape. In fact, part of the fiber is bent. In the future, the diameter measurement method of the bent fiber should be studied.

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