Characterization of fiber diameter using image analysis

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Abstract. Due to high surface area and porosity, the applications of nanofibers have increased in recent years. In the production process, determination of average fiber diameter and fiber orientation is crucial for quality assessment. The objective of present study was to compare the relative performance of different methods discussed in literature for estimation of fiber diameter. In this work, the existing automated fiber diameter analysis software packages available in literature were developed and validated based on simulated images of known fiber diameter. Finally, all methods were compared for their reliable and accurate estimation of fiber diameter in electro spun nanofiber membranes based on obtained mean and standard deviation.

1. Introduction
The production of nanofibers by electro spinning has recently become the most popular area of scientific and technological activities. Due to their extremely high specific surface area, they are an excellent materials for applications in filtration, agro textiles, and medical field [1]. Their efficient physical and mechanical performance depends on the structural characteristics (i.e. fiber orientation, fiber diameter, pore size, uniformity, fiber crimp, etc)[2–4]. The fiber diameter is one of the most basic structural characteristics to decide the higher specific surface area. The extremely small fiber size and random orientation of the nanofibers make the measurement of their diameter very difficult [5]. Usually, the routine measurements of fiber diameter and its distribution are carried out by manual method using ruler. However, this process is very time-consuming and not suitable for automated measurements during higher production rate of nanofibers in electro spinning. As a result, the search for automated fiber diameter measurement gained significant importance in recent years. The different algorithms have been developed for estimation of fiber diameter using image analysis [6–10]. For instance, Pourdeyhimi developed the distance transform method which estimated the fiber diameter from the distance of fiber centre line to the fiber boundary [11]. Later, Ziabari developed the modified distance transform method to overcome the limitations of Pourdeyhimi method of fiber intersection points [12,13]. The objective of present study is to compare the relative performance of different methods discussed in literature for estimation of fiber diameter. The existing automated fiber diameter analysis software packages available in literature were developed and validated based on simulated images of known fiber diameter. Therefore, the outcome of this work will provide an idea about simple, automated and efficient method of electro spun nanofiber diameter measurement.

2. Theory of the methods

2.1 Image processing operations
First of all, the acquired images are converted into gray scale images. The image processing operations are performed to improve the quality of gray scale images for further image analysis. The contrast
enhancement is carried out via adjusting the image intensity values. The two dimensional median filter is often applied to remove noise. The grayscale images are then converted into binary images using the initial segmentation. The advantage of obtaining binary image is that it reduces the complexity of the data and simplifies the process of recognition and classification. Thresholding is the simplest method of image segmentation, where each pixel in the source image is assigned to two or more classes. Therefore, thresholding is used to split an image into smaller segments, or junks, using at least one colour or gray scale value to define their boundary. In general, there are two types of thresholding algorithms. The global thresholding is the typical way, where a single constant threshold, usually selected by trial and error, is applied to segment the image. The global threshold is applicable when the intensity distribution of objects and background pixels are sufficiently distinct. There are a number of global thresholding techniques such as: Otsu, optimal thresholding, histogram analysis, iterative thresholding, maximum correlation thresholding, clustering, multispectral and multi thresholding. However, global thresholding is very sensitive to any inhomogeneities in the gray-level distributions of the object and background pixels. This effect can be eliminated through the use of a local thresholding scheme, where the image is divided into sub images which have fair homogeneities and different thresholds are applied to segment the sub images [14].

2.2 Pourdeyhimi method
In this method, a binary image is used to create a distance map and skeleton. The center points of the object which are equidistant from two closest points of the object’s boundary are obtained using medial axis transformation and set to as skeleton. The thinning operation removes the pixels on the boundary of the object without allowing it to break apart, thereby shrinking a thick object to a centrally located one-pixel width object. Further, the pruning operation cleans the short spurs generated on fiber surface. Therefore, the skeleton of an object is defined as the corresponding object with one-pixel width. The skeleton acts as a guide for tracking the distance transformed image and fiber diameters are measured from the intensities of the distance map at all points along the skeleton. The distance transform represents the minimum distance from each pixel belonging to an object to the background. The data in pixels may then be converted to the particular scale and the histogram of fiber diameter distribution is plotted.

2.3 Ziabari method
Ziabari et.al established a new method in which the problem associated with the short spurs and fiber intersections was solved [13]. A sliding neighborhood operation is used to identify the location of fiber intersection points. Further, the end points of skeleton are removed two times in order to get rid of the neighbor of intersection. In this way, the obtained skeleton after deleting the intersections is used as a guide for tracking the distance transformed image and the diameters are computed from the intensities of this image at all points along the skeleton.

3. Results and discussions

3.1 Manual method
The manual method normally consists of the following steps. First the scale is set. Then, pixels between two edges of a fiber perpendicular to the fiber axis are counted. The number of the pixels is then converted to the particular scale and the resulting diameter is recorded. On a typical image, the diameter of 100 fibers is measured and the histogram of fiber diameter distribution is plotted. Figure 1 shows the results of 25 observations for measurement of fiber diameter.
Figure 1. Fiber diameter estimation by manual method

3.2 Distance transform methods
Figure 2 (a) and (b) shows the SEM image of nanofibrous membrane. The different image processing operations were performed to improve the quality of image. The SEM image was then converted into binary image in Figure 2 (c) by Otsu thresholding operation.

(a). SEM image  
(b). Cropped SEM image  
(c). Otsu Thresholding

Figure 2. Basic image processing operations for distance transform method

3.2.1 Pourdeyhimi method. The skeletonization or thinning procedure was employed to obtain skeleton of objects (Figure 3). The skeleton was then superimposed on previous image to obtain the distance map. The fiber diameters are measured from the intensities of the distance map at all points along the skeleton. Figure 3d shows the histogram of fiber diameter distribution evaluated from Pourdeyhimi method [11].

(a). Distance map image  
(b). Skeleton image thinning
At the end, the validation of Pourdeyhimi method was performed on simulated image consisting of four intersecting fibers of known diameters (Figure 4). The good level of agreement was found between actual results and estimated results of algorithm. This confirmed successful development of algorithm for estimation of fiber diameter by Pourdeyhimi method.

3.2.2 Ziabari method. The modified distance transform method developed by Ziabari is similar to Pourdeyhimi method. However, it takes into account the intersection of fibers for more accurate estimation of fiber diameter. Figure 5 shows that all fiber intersection points have been successfully omitted during fiber diameter estimation. Then, the fiber diameters are measured from the intensities of the distance map at remaining points of the skeleton. Figure 5d shows the histogram of fiber diameter distribution evaluated from Ziabari method [13].
Figure 5. Fiber diameter estimation by Ziabari method

Finally, the reliability and accuracy of all the three methods was concluded for the estimation of fiber diameter in electrospun nanofiber membranes. Table 1 shows the mean, standard deviation and coefficient of variance for fiber diameter estimation based on these methods.

| Parameter               | Manual method | Pourdeyhimi method | Ziabari method |
|-------------------------|---------------|--------------------|----------------|
| Number of observations  | 25            | 16476              | 4364           |
| Mean fiber diameter (nm)| 375           | 567.3              | 424.4          |
| Standard deviation (nm) | 66.84         | 357.6              | 166            |

4. Conclusions
Fiber diameter is one of the most important structural characteristics in textile fibrous systems. The manual methods are often used for measurement of fiber. However, manual methods are not suitable for online quality control during high speed production of nanofibers. They are labor intensive, time consuming, operator-based and utilize only a low number of measurements. In this study, the concept of image analysis was used for automated measurement of fiber diameter in electrospun nanofibrous membranes. The distance transform methods suggested Pourdeyhimi and Ziabari were compared for their reliability, accuracy and simplicity of measurements. The successful development of algorithms was confirmed by validation of these methods on simulated images of known fiber diameters. From
statistical analysis, more accurate estimation of fiber diameter was confirmed in case of Ziabari method than the Pourdeyhimi method. This was attributed to omission of fiber intersection points during diameter measurements. Nevertheless, Pourdeyhimi and Ziabari methods failed to accurately estimate the fiber diameter during fiber beading, fiber overlapping, co-joined fibers, or fiber crossovers. Therefore, further research is required to overcome these limitations by development of versatile and robust new algorithm.

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