Summary Sheet

- **Paper citation:**

M. Eldessouki, S. Ibrahim, and J. Militky, "A Dynamic and Robust Image Processing Based Method for Measuring Yarn Diameter and Its Variation," *Textile Research Journal*, vol. 84, no. 18, pp.1948-1960, 2014, DOI: 10.1177/0040517514530032.

- **Targeted problem:**

Microscopic method for measuring the yarn diameter is a ***static*** in nature as it collects data on ***short distances*** along the yarn length, on the other hand, the data collected by commercial methods are treated in a ***black box system*** without clear understanding of the results

- **Objective(s):**
  - Develop a system of high speed camera for capturing the yarn running in speeds comparable to those of commercial instruments
  - Develop a robust algorithm with little computation requirements for analyzing the acquired images
  - Treat the collected data in a "transparent box system" based on time-series analysis with a clear interpretation of the results
  - Compare the methods performance with commercial devices

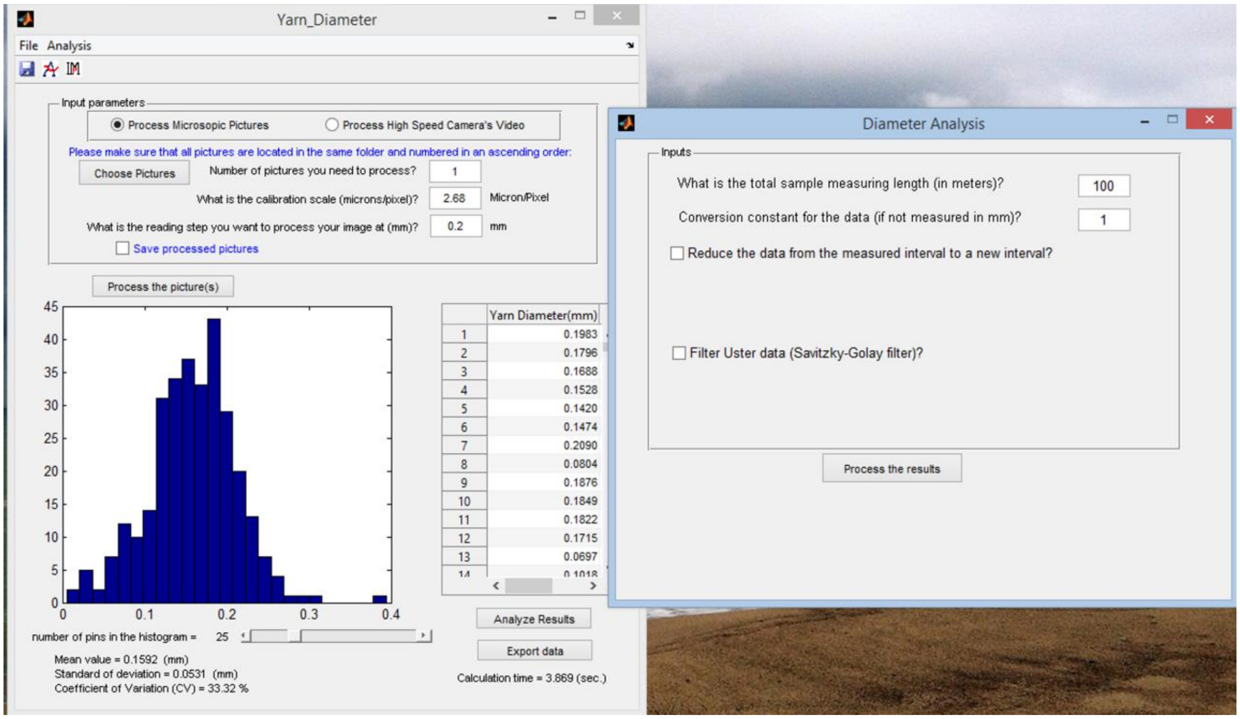
- **Materials scope:**
  - Two cotton yarns of different counts were produced using the ring spinning technology
  - One of the yarns was has slubs along its length and selected to provide more information about the system performance with variable diameters

- **Computation method:**
  - Yarn images were analyzed using a newly and simple developed algorithm
  - Measured diameters were analyzed using different statistical and time series methods to detect the short-term, the long-term, and the periodic variations in the yarn diameter

- **Paper significance:**
  - The image analysis method developed in this work is a new simple method that is computationally inexpensive and can handle massive amount of images within a reasonable time.
  - The developed data-treatment algorithm is powerful enough to handle data collected from the image analysis method or to handle the raw data that might be obtained from the commercial measuring instruments and standardize the results with a transparent explanation

- **Software**

A software program with a user-friendly GUI was developed for this work and named DiaLib®. The DiaLib® consists of two modules for image analysis and for data treatment. The software is available on the accompanied CD with a tutorial video demonstration. The program also has some examples on the CD so it can be tested. The program GUI is shown below:


Yarn_Diameter
File Analysis
Input parameters
Process Microsopic Pictures
Process High Speed Camera's Video
Please make sure that all pictures are located in the same folder and numbered in an ascending order:
Choose Pictures
Number of pictures you need to process?
1
What is the calibration scale (microns/pixel)?
2.68
Micron/Pixel
What is the reading step you want to process your image at (mm)?
0.2
mm
Save processed pictures
Process the picture(s)
Yarn Diameter(mm)
1 0.1983
2 0.1796
3 0.1688
4 0.1528
5 0.1420
6 0.1474
7 0.2090
8 0.0804
9 0.1876
10 0.1849
11 0.1822
12 0.1715
13 0.0697
number of pins in the histogram =
25
Mean value = 0.1592 (mm)
Standard of deviation = 0.0531 (mm)
Coefficient of Variation (CV) = 33.32 %
Analyze Results
Export data
Calculation time = 3.869 (sec.)
Diameter Analysis
Inputs
What is the total sample measuring length (in meters)?
100
Conversion constant for the data (if not measured in mm)?
1
Reduce the data from the measured interval to a new interval?
Filter Uster data (Savitzky-Golay filter)?
Process the results

A Dynamic and Robust Image Processing Based Method for Measuring The Yarn Diameter and Its Variation

Mohamed Eldessouki[1,2], Sayed Ibrahim[3], Jiři Militky[1]

[1]Technical University of Liberec, Faculty of Textile Engineering, Materials Engineering Department, Liberec, Czech Republic

[2]Department of Textile Engineering, Faculty of Engineering, Mansoura University, Mansoura, Egypt

[3]Technical University of Liberec, Faculty of Textile Engineering, Textile Technology Department, Liberec, Czech Republic

Abstract

The yarn diameter is an effective property in determining fabric structure and processing settings. There are different systems of measuring the yarn diameter; among them is the image analysis of the yarn's microscopic images. This method is considered to be more precise than other methods, but it is "static" in nature as it measures the property at scattered intervals and does not reflect the continuous variation of the yarn diameter. The goal of the current work is to measure the yarn diameter and its variation over a long length of yarn at fixed intervals to consider the "dynamic" change in the property. To achieve this goal, a high-speed camera (HSC) with a proper magnification was used to capture the images of the yarn and a new robust algorithm was developed to analyze the massive amount of yarn pictures in a reasonable time. The collected data for the yarn diameter were analyzed and compared to the results of the commercial Uster Evenness Tester IV. The results of the HSC were very comparable to the results of Uster and they were able to detect the short-term, the long-term, and the periodic variation of the yarn diameter.

1. Introduction

Yarn diameter is an important parameter that is used in all the calculations and modeling of fabric parameters [1] such as weave angle, yarn densities in warp and weft directions, yarn crimp ratio, cover ratio, fabric weight, and fabric volumetric density. The yarn diameter has also a direct impact on some of the measured fabric properties that affect the fabric dimensional and mechanical parameters [2]. Fabric performance and comfort depend on the yarn diameter as it correlates to the fabric air and water permeability. The settings of winding machines (e.g. cleaning knife) and most of the machines in the subsequent processes depend on the yarn diameter. On the other hand, the "exact" measurement of the yarn diameter is very difficult because of the inherent yarn unevenness and irregularity. That leads the textile specialists to talk about the yarn "size" or "count" instead of its "diameter". However, yarn count may not precisely indicating the yarn diameter as two yarns with the same count may have two different diameters due to the changes in other parameters such as the fiber density and the yarn twist factor. Therefore, a good method of measuring the yarn diameter should maintain two basic features; it should measure the diameter with high precision and accuracy. It also should be able to determine the irregularities that occur in diameter at different bases (short and long term variations as well as the periodic variations).

The principles of measuring the yarn diameter can be classified [3] into four main categories that are summarized with their pros and cons in Table 1. These methods are:

- ***The capacitive measurement***: this is an indirect method of measuring the variation in yarn linear density (yarn count) which correlates to the yarn diameter through empirical relations from which the variation in yarn diameter can be calculated. The major drawback of this method is the indirect measurement of the yarn diameter (in fact, the mass variation is measured not the diameter but due to the high correlation between both parameters, it is possible to measure one parameter and infer the other [4, 5]). This method also depends on the testing environmental conditions because the capacitors are usually affected by the temperature and humidity. The resolution of this method is relatively low where the capacitors sample the data every 8mm (e.g. old versions of Uster tester).

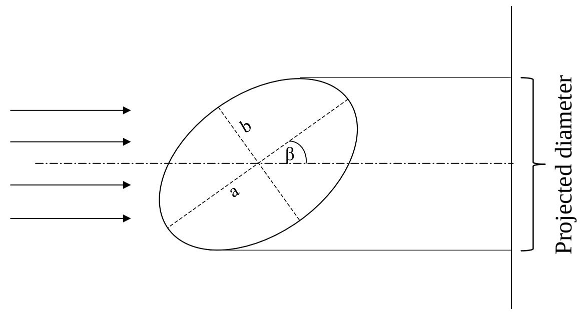


Figure 1. Schematic representation of the optical yarn diameter measurement system

- ***The optical measurement***: this method is widely common [6] in commercial devices where high resolutions (e.g. 0.25 mm) can be obtained. This method determines the diameter after shedding a beam of laser light on the yarn and analyzing its projected image on a light sensor, Figure 1. The results of this method are highly dependent on the direction (the angle β) of the yarn as the projected image of the elliptical shape of the yarn may be larger or lower than the actual diameter. This method does not affect with the testing humidity or the fiber blend variation [7] although it might be affected with the presence of lint and yarn hairiness. During these measuring methods, the yarn exists under a slight tension in the longitudinal direction which causes a compression in the transverse direction and may lead to changes in the measured diameter.

- ***The mechanical (electro-mechanical) measurement***: in this method, the yarn runs between two sensors (fixed and freely moved) where the movement of the freely moved sensor is magnified for measuring the diameter. These sensors are implemented in different ways (cylinders, flat surface…etc) among them a device similar to the tongue and groove mechanism used on drawing frames [3]. The yarn passes through the grove and the tongue is attached to an arm that works as displacement amplifier to record the yarn diameter and its variations.

- ***The small scale microscopic measurement***: This laboratory method is, principally, an optical method but it can be distinguished from the other optical methods by its small scale of measurements where the yarn diameter is measured in two directions; the cross section or the longitudinal view of the yarn [8]. The cross section of the yarn should be carefully cut at different positions and the diameter can be captured under the microscope with an appropriate magnification. Similarly, the yarn diameter is measured from the longitudinal projections of the yarn under the microscope at randomly different positions to account for the elliptical shape of the yarn [9]. Measurements can be done on the computer by a visual inspection or automatically using some image analysis techniques.

Table 1. Advantages and disadvantages of the methods for measuring yarn diameter

	Advantages	**Disadvantages**
Capacitive	- Works with the common yarn irregularity measurement systems - Primitive method	- Low resolution - Depends on the testing environment - Affected by other fiber properties (e.g. material type, fineness, specific density) and yarn parameters (e.g. twist, production technology)
Optical	- High resolution - Does not depend on testing environment - Simple and fast	- Measures the projected diameter not the real diameter - Yarn under tension reduces the measured diameter - Affected with the lint and hairiness
Mechanical	- Direct contact with the yarn	- Depends on the applied load during measurement
Small scale measurement	- Precise method - Measures the actual diameter	- Time consuming and tedious method - Not suitable for practical application in production scales

The microscopic evaluation of yarn diameter is preferred for academicians in laboratories for its accuracy and it is used to calibrate the other methods. This method, however, is time consuming and needs many repeating samples which makes it unsuitable for practical testing in production environments. It is also important to notice that the measurements of this method are "static" as they give information about the yarn at "*scattered*" points across the length of the yarn. This means; it does not capture the continuity of the variation in the measured property along the yarn and cannot usually detect the short-term, the long-term, or the periodic variation of the yarn diameter.

This work aims at tackling the problems of the microscopic evaluation method and presents a new computer vision based system to measure the yarn diameter and its variation utilizing video processing and analysis algorithms. A high speed camera (HSC) is used to capture the yarn images and it was used to allow testing speeds comparable to speeds of the known commercial devices. A new image analysis algorithm is developed to enhance the captured images by eliminating the yarn hairiness and hence to obtain the yarn diameter. The continuity of the obtained results at fixed interval allows their treatment as time series which unveils some of the yarn characteristics that produced from the commercial instruments. Two case studies are used in order to validate the presented system results; one of them is a regular ring-spun yarn and the other is a slub-yarn. Both yarns are tested simultaneously on the presented system and on the Uster Evenness Tester IV.

2. Experimental Setup

2.1. Computer vision setup

Pre-investigation of the system and the analysis algorithm was initially performed using yarn samples evaluated under the optical microscope. Olympus microscope was used with an automated stage to capture the yarn images along a certain distance with a magnification scale of 2.68 µm/pixel. The setup of the microscope is shown in Figure 2 with the motorized stage and the digital camera that is connected to the computer. The microscope system captures a longitudinal view of the yarn then the stage moves automatically with a predefined distance to capture another image. The obtained images were stitched and superimposed together to form a single picture of the whole yarn.

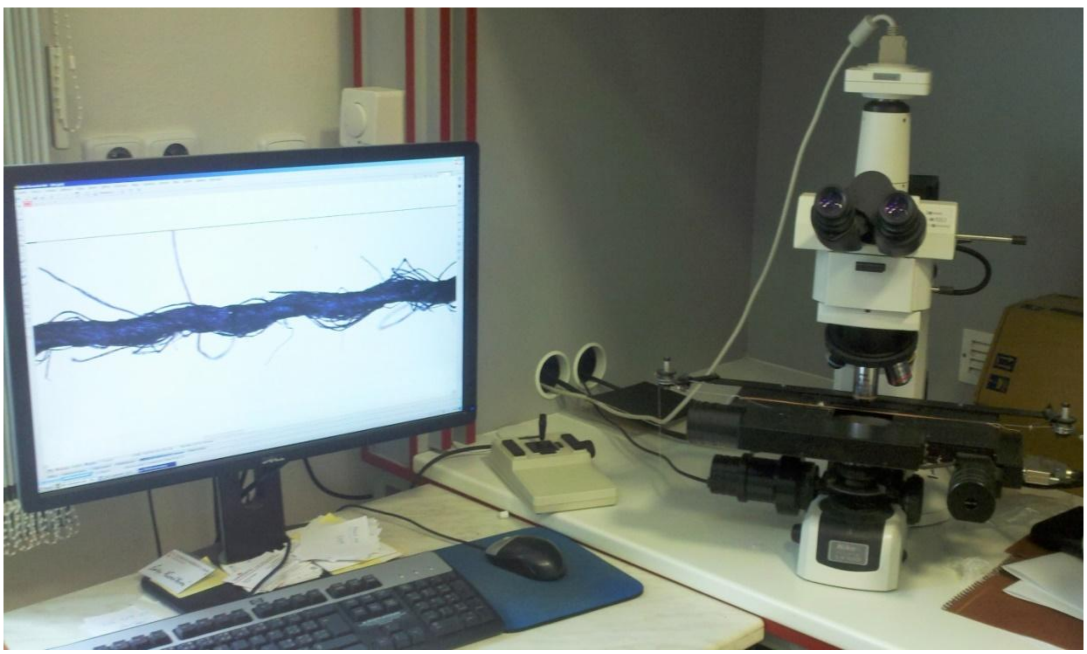


Figure 2. Microscopic setup with a motorized stage and CCD camera connected to the computer

Because of the slow image acquisition with the automated microscope, alternative systems of acquisition were considered. A video camera with appropriate magnification lenses was applied; however, the yarn speed for this camera setup was about 15 m/min which is less than the practical testing speeds of the commercial instruments. To run the yarns at 100 m/min (which is the testing speeds of other instruments such as Uster evenness tester IV), a high speed camera (HSC) was used. Olympus i-speed 3 high speed camera was installed with appropriate macro-lenses. The HSC captured yarn images with a speed of 150 frames per second (fps), the used shutter speed was 200X, and the resolution of individual frames in the recorded video was 1280x1024 pixels with a magnification scale of 10.2 µm/pixel. The yarn was lighted with a special Xenon lamp directed with an optical fiber to the HSC shooting zone. To avoid the effect of tension changes during the experiments, the yarn was running in front of the camera under constant tension using the tension compensation mechanism of Lawson Hemphill Constant Tension Transport (CTT) tester. The introduced computer vision system for measuring the yarn diameter (that includes the video camera setup with the analysis software) was assigned a name DiaLib®.

2.2. Tested samples:

Two yarn samples were examined and analyzed using the suggested method and the results were verified against the measurements on the commercial Uster evenness tester IV. The first yarn sample is a normal ring-spun 100% cotton yarn with a count of 20 tex. The second yarn sample is a cotton slub-yarn produced by deliberately changing the draft on the spinning frame. The yarn count was 23 tex and the slub thickness was designed to be as twice as the yarn original diameter. The slubs were distributed across the yarn in two populations with slub-lengths of 50 mm and 100 mm. The inter-slub separation distance was designed to be 150 mm. The yarn was tested on Uster evenness tester IV for its diameter and irregularity and the images of the yarn were captured using the high speed camera. The yarn speed during testing on the Uster and the HSC was 100 m/min.

3. Methods

3.1. Image processing and analysis:

The longitudinal view of the yarn sample was acquired with a proper magnification using a digital camera connected to the computer. The acquired images were converted to binary with a suitable threshold to allow faster processing. The yarn diameter is calculated by counting the pixels belonging to the yarn body at specified intervals. The existence of yarn hairiness with protruding fibers does not allow the direct and automatic finding of the yarn limits (where the diameter can be measured) because those protruding fibers will be outside the actual diameter. Therefore, the automatic measurement of the yarn diameter is faced with three obstacles; firstly, the exclusion of the yarn hairiness from the yarn body. Secondly, the filling of the voids inside the yarn body that occur during the conversion to binary images (due to the shading differences in the microscope images). Thirdly, the standard algorithms for edge detection (to remove the hairiness) and object filling (to remove the voids) are relatively slow (as they convert the image back and forth between its spatial and spectral domains) and there is a need to increase the speed of the processing algorithm. These obstacles will be folded many times in accordance with the interval distance between the measurements and the number of the images to be processed. For example, there is about 350 slices in an image of a yarn with length ≈ 7 cm and interval between readings of 0.2 mm, and this number reaches many thousands for longer yarn samples.

To face these challenges, a new algorithm was developed to be robust with the increase in number of pictures and sampling points. To find the yarn body in an image (let us call it I1), two other images of the yarn were created by translating the yarn image in the vertical direction with distances $\pm\delta$ (let us call the created shifted images; I2 and I3). Then, the three images are added together and the summation matrix is logically compared to a certain threshold to produce a binary image with filled yarn body and trimmed off the majority of yarn hairiness.

To demonstrate the algorithm, an example is shown in Figure 3 with a small scale matrix with a height of 20 pixels (while actual yarn images have a height of 1024 pixels). The example in Figure 3 shows one vector (a column that can be called C1) that represents what is extracted from the binary matrix of the yarn image at a certain cutting interval, and the same calculations can be extended for all intervals in the yarn image. The example shown in Figure 3 represents the black background with zeroes and the white elements of the yarn with ones. The representation vector C1 corresponds to a slice of the image where the yarn body is represented with a series of ones (including some voids of zeroes) and a part of the protruding fiber at the top of the vector. This vector was shifted upward with a distance (δ) of 2 pixels (which resulted in another vector that can be called C2) and shifted downward with the same δ (to result in a third vector C3). The vector C4 is the summation of C1, C2, and C3 then it is logically compared to consider the positions with numbers less than or equal to one as background (substituting a value of zero at these positions) and the positions of values greater than one to be foreground (substituting a value of one). The resulted vector C5 shows the solid yarn body without voids or yarn hairiness from the protruding fibers.

To compare the suggested algorithm with the "traditional" edge detection techniques, it is important to understand how these techniques work. The traditional edge detection techniques generally depend on converting the image from its spatial domain into frequency domain to apply some filters on the image then the image is converted back to its spatial domain. After this process, the detection algorithm applies some programming loops to determine the yarn boundaries and remove the hairiness. These traditional methods are computationally expensive and depend on the available hardware resources in completing these tasks. Our suggested method, however, analyzes pictures in their spatial domain only and avoids the loops that consume the computer resources. As the time for any image processing method depends on the used algorithm and the available hardware resources, the suggested system used a personal computer with an Intel core i3 processor to analyze ≈ 10000 pictures in ≈ eight minutes.

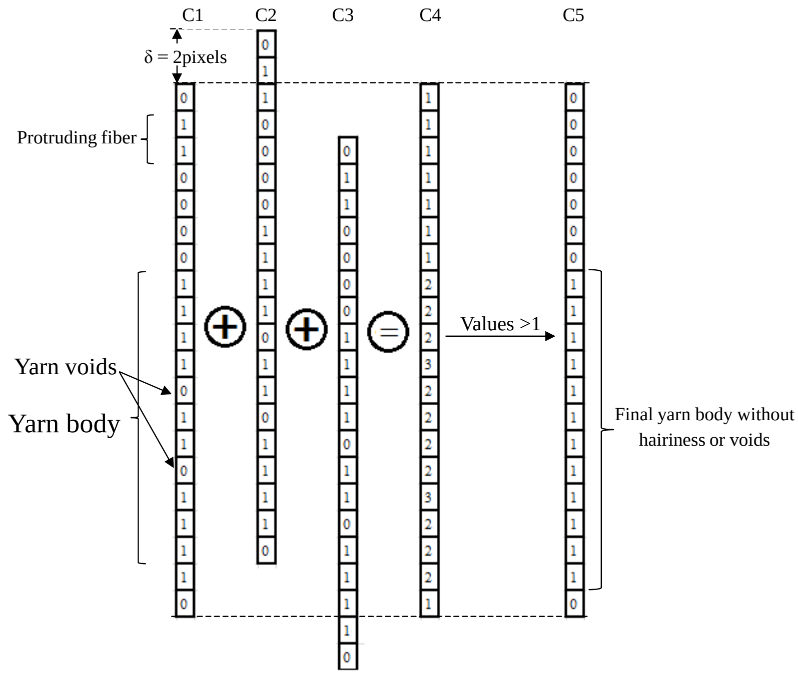


Figure 3. Example of the suggested algorithm to remove hairiness and fill-in yarn voids to find yarn body and diameter

Although this algorithm is relatively fast and robust compared to the standard edge detection and image filling algorithms, it has some drawbacks and errors that may occur during the processing. These errors result from the dependency of the algorithm on the deliberate choice of the image shifting (δ) and on the position of the protruding fibers and voids (which are random). After considering different values for the image shifting (δ) and its effect on the calculation accuracy, it was found that a δ value is approximately equal to the thickness of the protruding fiber is a good choice in most cases. Therefore, the value of δ is calculated during the analysis based on the magnification scale and the fiber's average diameter that are given by the user. To illustrate the errors that may occur, Figure 4 shows a vector from the yarn image similar to the one shown in Figure 3 with a minor change in the position of the protruding fiber which resulted in an error as indicated in C5 by considering one extra pixel as part of the yarn body. A similar error can occur for consecutive voids with a close proximity. Considering the image scale (where one pixel is about 2.6 µm for the microscopic images to 10 µm for the camera images) and the averaging of the thousands of readings to calculate the yarn diameter, the calculation error of this algorithm can be found in the order of 10^{-6} mm per pixel. This error order is relatively small and does not significantly affect the final results of yarn diameter.

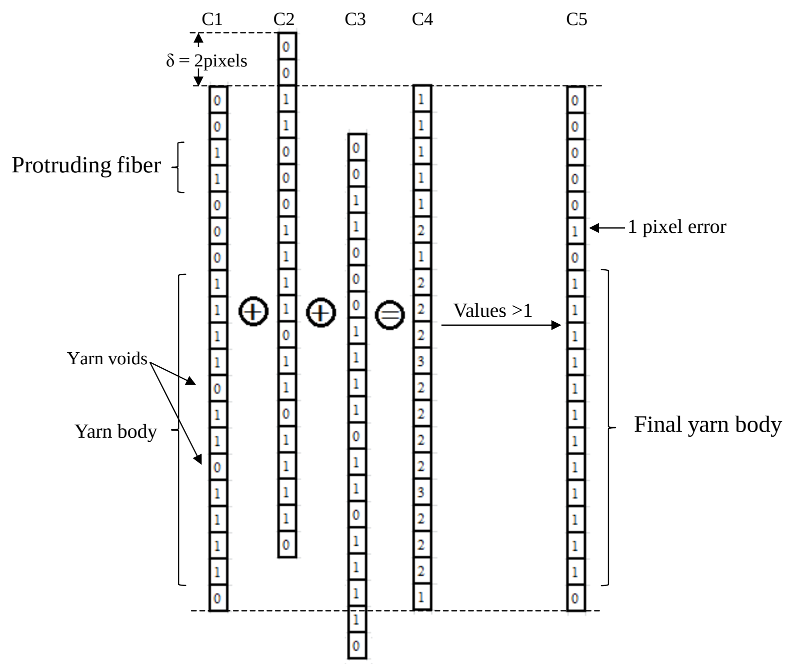


Figure 4. Example of the suggested algorithm with an error in the hairiness removal

3.2. Data analysis and parameterization:

The data obtained from the analysis of the high speed camera (HSC) images are taken at regular intervals (space and time intervals) which allow the data to be treated as time series. Beside the normal statistics that can be derived for any set of data, the discussion here will focus on the parameters that depend on the data continuity to demonstrate the advantages of the introduced procedure (with the dynamic measurement of the yarn) over the static procedures.

The length-variance curve:

The length-variance curve (LVC) determines the relationship between the variability of the yarn diameter and the measurement intervals. The variability (*CB*) is expressed as the coefficient of variation and can be measured at a certain yarn cut length (λ) according to [10]:

$$CB(\lambda) = \frac{s(\lambda)}{\bar{x}(\lambda)} \qquad (1)$$

Where, $s(\lambda)$ denotes the standard deviation of yarn diameter and $\bar{x}(\lambda)$is the average value at a given cut length λ. The "cut length" represents the distance between two consecutive diameter readings on the measurement system and these calculations are repeated at different cut lengths to construct the LVC.

Deviation rate:

The deviation rate (*DR*) measures the frequency (the rate of occurrence) for a diameter value to deviate from the yarn mean diameter plus or minus a certain sensitivity limit (α). For the deviation rate calculation, the function $p(n,\alpha)$ should be calculated to allow the frequency calculation. This function can be defined as [11, 12]:

$$p(n,\alpha)=\begin{cases}1 & f(x_n)\geq(1+\alpha)\bar{\mu} \\ 0 & (1-\alpha)\bar{\mu}< f(x_n)<(1+\alpha)\bar{\mu} \\ 1 & (1-\alpha)\bar{\mu}\geq f(x_n)\end{cases} \quad (2)$$

The deviation rate can be calculated from the function $p(n,\alpha)$ according to the relation:

$$DR_\alpha[\%]=\frac{\sum_{n=1}^{N}p(n,\alpha)}{N}*100 \quad (3)$$

Where n is an index, α is the sensitivity limit, $f(x_n)$ is the diameter value, $\bar{\mu}$ is the mean diameter of the yarn sample, and N is the total number of readings.

Absolute mean deviation

The absolute mean deviation (U%) is a commonly used term to define the mass irregularity of yarns and can be used to define the irregularity in diameter as well. It can be calculated for a series of diameter readings (x_n) using the relation:

$$U[\%]=\frac{\sum_{n=1}^{N}|x_n-\bar{\mu}|}{N*\bar{\mu}}*100 \quad (4)$$

Integral deviation rate

The integral deviation rate (*IDR*) accounts for the diameter's absolute mean deviation at certain sensitivity limit (α) and it can be considered as a generalization formula for the U% (where $U\% = IDR$ at α=0). The starting function for the *IDR* calculation is the function $y(n)$, similar to the frequency function $p(n,\alpha)$, where:

$$y(n,\alpha)=\begin{cases}|f(x_n)-(1+\alpha)\bar{\mu}| & f(x_n)\geq(1+\alpha)\bar{\mu} \\ 0 & (1-\alpha)\bar{\mu}< f(x_n)<(1+\alpha)\bar{\mu} \\ |f(x_n)-(1-\alpha)\bar{\mu}| & (1-\alpha)\bar{\mu}\geq f(x_n)\end{cases} \quad (5)$$

Then, the IDR can be calculated according to:

$$IDR_\alpha[\%]=\frac{\sum_{n=1}^{N}y(n,\alpha)}{N*\bar{\mu}}*100 \quad (6)$$

Autocorrelation function

Autocorrelation is an expression for the correlation of a time series with its own past and future values. The autocorrelation function (ACF) that measures the correlation of a data series $x(n)$ with itself shifted by some delay (lag) m can be calculated from the auto-covariance function[13]:

$$C(m)=\frac{1}{N-m}\sum_{n=1}^{N-m}(x(n)-\bar{\mu}).(x(n+m)-\bar{\mu}) \quad (7)$$

And the sample auto-correlation function at the lag m can be calculated as:

$$\rho(m)=\frac{C(m)}{C(0)}, \qquad m=1,2,3,\ldots.M<N \quad (8)$$

4. Results and discussion

It is worthy at the beginning of the discussion to clarify four points regarding the suggested algorithm and the selected yarn samples. First, the proposed method as well as all methods that measure the diameter with a single yarn projection (i.e. using only one camera or sensor) work under the basic assumption that: during the measurement of longer lengths of yarn, the yarn rotates around its axis and the huge amount of collected readings will eventually account for the elliptical shape of the yarn. Second, the choice of the slub-yarn as a second case study versus the normal ring-spun yarn is based on the continuous and periodic variation of yarn diameter in these yarns which should clarify the performance of the proposed system in measuring the yarn diameter and detecting the different types of its variation.

Third, the results of the HSC tested yarns were compared to Uster Evenness Tester IV although the most recent version of Uster Tester V has a special configuration for measuring the slub-yarns and gives more detailed and relatively precise information about the special structure of these fancy yarns. This study, however, meant to verify the validity of the applied algorithm even if it does not compete with the advanced hardware and software implemented by Uster. Four, Uster Tester is the most used instrument in industry and is able to deal with the measurement as a function of time and results in useful information such as LVC, spectrogram…etc. On the other hand, the suggested algorithm is relatively cheap and "transparent box" system that enables us to verify the results obtained from Uster and other instruments that work on the optical principle. Also, the suggested algorithm allows functions and parameters that are not produced by commercial instruments to be calculated (e.g. autocorrelation function, fractal dimensions,...etc) and these parameters are out the scope of the current study.

4.1. Microscopic images

The yarn samples were tested on the microscope setup where the individual captured frames represent a length of about 2.9 mm of the yarn length. The microscope software applies a picture stitching algorithm (for a collection of about 25 pictures) that considers the overlapping of the pictures to create a single image (of about 7 cm) as shown in Figure 5-a. The operation was repeated for a total sample length of 3 m. The individual pictures (for the 7 cm) were processed and an example for a magnified part of the yarn is shown in Figure 5-b. The yarn diameter can be calculated at any required reading interval where the minimum interval is about 2.68 µm (that is equivalent to 1 pixel). A yarn image that was processed at an interval of 0.2 mm is shown as a superimposed image of the actual yarn and the detected boundaries in Figure 5-c where the white parts of the vertical lines represent the detected yarn boundaries at each interval. It can be seen in the processed image that the automated algorithm was capable of detecting the yarn boundaries and considering the yarn body despite of the differences in the gray levels inside the yarn. The method, however, failed to remove the whole protruding fiber as circled in Figure 5-c (the first reading to the right). The reason for the system to consider this hairiness inside the yarn diameter is, partially, because of its close proximity to the yarn body and its positioning in a vertical way (which resulted in more pixels in the cross-section compared to the positioning of horizontal fibers). After all, the method was able to remove about half of the circled protruding fiber and the remaining part is much less than 10% of the yarn diameter which makes this error almost negligible after averaging the thousands of reading.

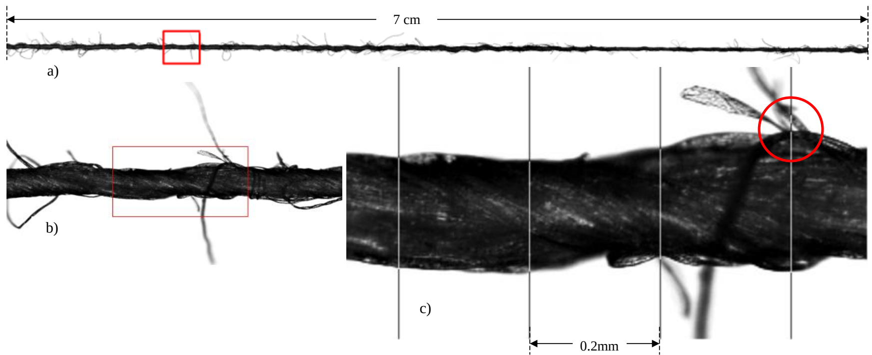


Figure 5. a) Longitudinal view of the yarn as captured under the microscope; b) the magnification of the window drawn in a; c) a magnification of the window drawn in b with illustration of the diameter measuring intervals

4.2. The high speed camera

A 100 m of the each yarn sample (a one minute run) was recorded and the sampling of the yarn diameter from the video was flexible to be adjusted at any interval (with a minimum distance of about 0.01 mm between diameter readings). To compare the HSC with the USTER tester results the measurement interval was adjusted to 0.3 mm to match the interval used in Uster measurements. Two sets of data produced from the HSC with a set of measurement at 0.3 mm and another set of readings that averages every 8 mm to match the results produced by Uster tester. Once videos were processed and the results from HSC were collected, the analysis was performed to produce the statistical and spectral features of the yarn diameter. We should point out that: Uster tester uses two perpendicular cameras to measure the yarn diameter and reports two results; the one obtained from the two cameras and the other from values measured using one camera.

4.2.1. Basic statistics and short-term variation

Table 2. Uster and HSC diameter results for the tested yarn samples

		Uster		**HSC**	
		0.3mm	**8mm**	**0.3mm**	**8mm**
Normal yarn	**Average diameter (mm)**	0.22	0.218 (2D*)	0.235	0.235
	CV (%)	18.68 (2D) 19.82 (1D**)	13.40 (2D)	23.34	13.53
Slub-yarn	**Average diameter (mm)**	0.26	0.259 (2D*)	0.239	0.24
	CV (%)	33.47 (2D) 34.01 (1D**)	31.58 (2D)	36.86	30.33

* Values measured using two perpendicular cameras

** Values measured using one camera

The results of both the Uster tester and the HSC are summarized in Table 2 at the two measurement intervals 0.3 and 8 mm for both yarn samples. The average yarn diameter for both yarn samples is comparable when measured using Uster and obtained from the suggested method. The variability of values, on the other hand, as expressed in terms of the coefficient of variation (CV) is slightly different especially as measured at short intervals of 0.3 mm. It is also observed that the CV values are generally higher at short measurement intervals; that is expected as more variability is encountered at these lengths. This increase is also in agreement with the behavior of the length variation curve where higher variation is usually found at shorter measuring lengths. Although the slub-yarn has two different diameters as can be clearly seen in the bimodal histograms of Figure 6, the results of Uster report a single value for the diameter (with a high variation) which is the mean of all values if considered as a normal distribution. The diameters calculated from the high speed camera are also shown in Figure 6 with a bimodal histogram for the slub-yarn sample. The theoretical normal distribution curves calculated from the HSC analysis are shown in the figure with mean values relatively close to the data obtained from Uster. The availability of the raw data from the HSC allows the analysis of the two averages of the bimodal distribution for the slub-yarn. The Hartigan's DIP method [14, 15] was used for testing the unimodality and the finite mixture distributions method [16-18] was applied to separate the bimodal curve. Analysis of the bimodal distribution indicates that the first mode is 0.301 mm (standard deviation 0.066 mm) and the second mode is 0.192 mm (standard deviation 0.024 mm).

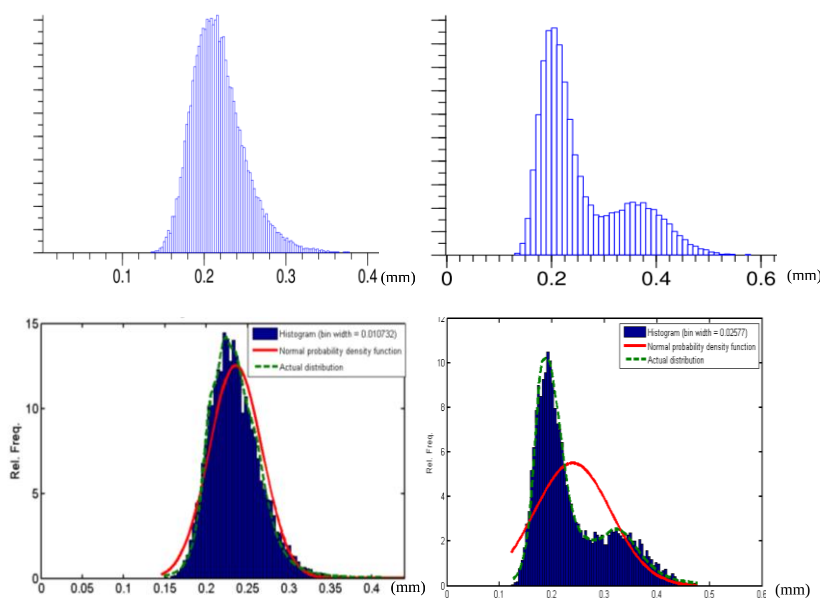
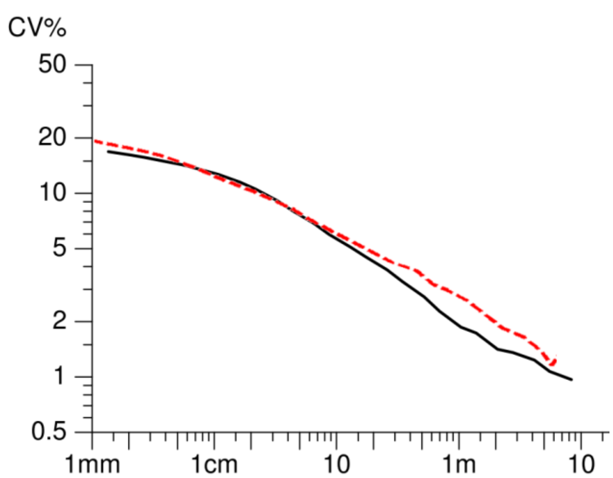


Figure 6. Histogram for the yarn diameter measured by Uster (top) and produced from the analysis of HSC (bottom) for the normal yarn (left) and the slub-yarn (right)

4.2.2. Long term variation

The long term variation in the yarn diameter can be detected using the length-variance curve (LVC). The application of the image processing allows the determination of the yarn diameter at different intervals which permitted the construction of the LVC. The LVC for the tested yarns are shown in Figure 7 as produced from the applied algorithm and compared to the curve obtained from Uster evenness tester. The theoretical LVC for an ideal yarn can be represented by an inclined straight line (on a diagram with double logarithmic scale) and any deviation from the ideal line corresponds to a long term variation. It can be seen from the figure that the results of the HSC are very comparable to the results of the Uster tester and the LVC curve for the normal yarn is almost straight while being curved for the slub-yarn. The LVC is very useful in comparing the regularity of different yarns and the similarity between the curves produced from Uster and from the HSC is an evident for the validity of using this method in the yarn diameter measurement for long lengths.



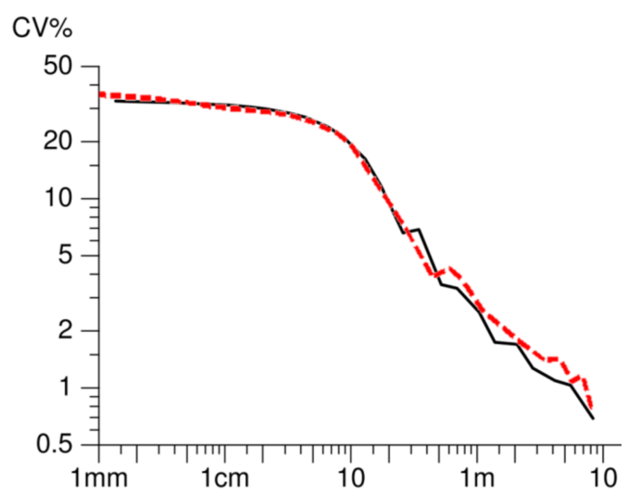


Figure 7. Length variation curve (LVC) for the yarn diameter measured by Uster (solid black) and produced from the developed HSC analysis (dashed red) for the normal yarn (left) and the slub-yarn (right)

The deviation rate percentage refers to the cumulative yarn length with diameters above or below a certain limit defined as a percentage of total sample length [19]. For example, if 30% is the calculated *DR* at α=10% for a yarn with average diameter *d*, it means that 30% of the total tested length has a diameter bigger than 1.1*d* or smaller than 0.9*d*. The deviation rate measured by Uster is illustrated in Figure 8 as well as the values calculated from the HSC. The curves were calculated at different measurement lengths where the *DR*% was calculated at the original interval of 0.3mm and was smoothed for lengths λ = 1.5, 3, and 10 m of the yarn samples. By smoothing we mean the averaging of the data and consider one reading for each length λ. For example, at λ=1.5 m an average for 5000 readings from the readings with λ=0.3 mm were considered as one reading in the subsequent calculations. The curves shown in Figure 8 for the HSC were calculated as α changes in the interval [-40:100] and demonstrated for the slub-yarn in the interval [-30:50] for illustration purposes. The general trend of the calculated curves is similar to those produced by

Uster although the slight differences in numbers are found and can be attributed to the differences of the individual readings. The IDR is also shown in Figure 8 with a similar trend albeit the calculated *IDR*% at α=0 for the different curves are more separated than the same values of *DR* at the same level of α.

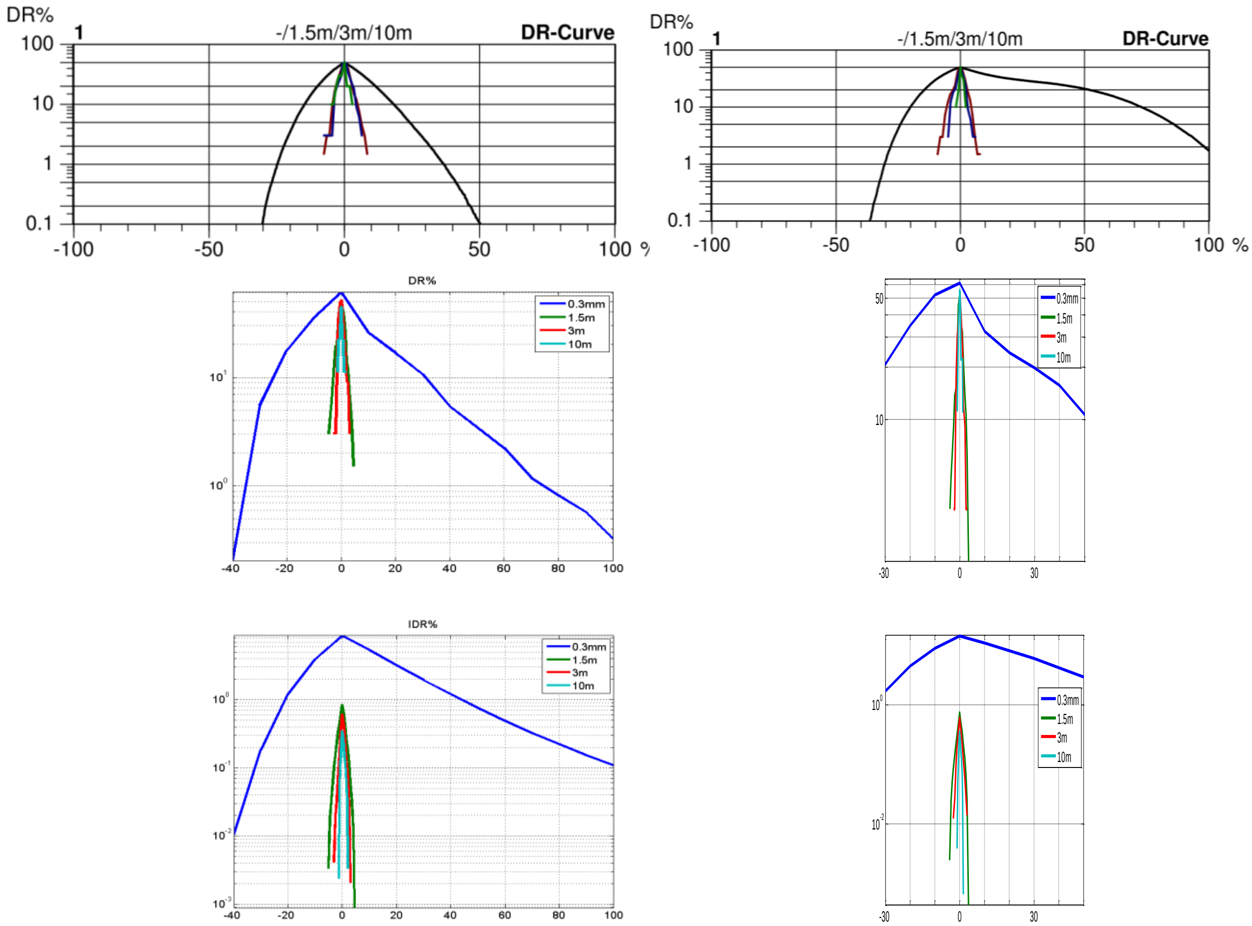


Figure 8. The DR% (middle) and the IDR% (bottom) of yarn diameter as calculated from the HSC algorithm and compared to the DR% obtained from Uster (top) for the normal yarn (left) and the slub-yarn (right)

4.2.3. Periodic variations

The periodic variations can be detected using the spectrogram. Although spectrograms are "commonly" used to demonstrate the mass periodic variability, Uster Tester also "optionally" produces a similar spectrogram for the diameter variability. The rules applied in explaining the mass spectrogram are similarly used in explaining the diameter spectrogram. The yarn diameter spectrograms which are illustrated in Figure 9as obtained from Uster tester for both yarn samples. The spectrograms produced from the data obtained from the HSC image analysis are shown also in Figure 9which indicates a relatively high similarity with the fault peaks detected by Uster for the slub-yarn sample while no similarity can be detected for the normal yarn. The contrast between the HSC calculated spectrograms for both samples is very indicative for the existence of periodicity along the yarn samples. For the slub-yarn, where periodic variation exists, the HSC's spectrogram has dominant peaks that match the ones obtained from Uster, while in the normal yarn, with little periodic variation, the calculated spectrogram does not have such dominant peaks. The peaks shown on the HSC's spectrogram for the normal yarn are illusive as the vertical scale of the curve is very small compared to the slub-yarn's calculated curve. The four dominant peaks on the spectrogram produced from the HSC for the slub-yarn sample are located at about 0.07, 0.13, 0.25, and 0.42 m which can be found on the Uster spectrogram at the same wavelengths. The peak at the wavelength around 7.5 cm can be attributed to mechanical faults and drafting waves and the peak that is located around 13 cm can be attributed to the inter-slub distance and the peak around 25 cm can be attributed to the pattern of the long slub (10 cm) plus its inter-slub distance (15 cm). The peak at 45 cm can be attributed to the whole repeat for the pattern of the two slub populations (that is 5+15+10+15 cm).

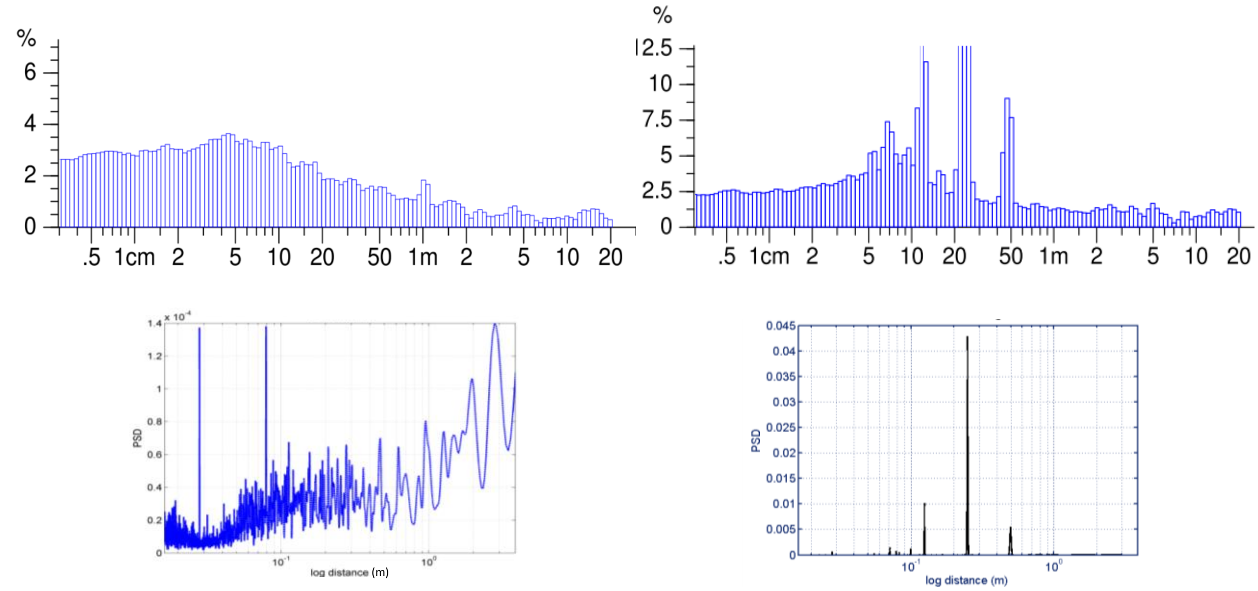


Figure 9. Spectrogram for the yarn diameter measured by Uster (top) and produced from the developed analysis (bottom) for the normal yarn (left) and the slub-yarn (right)

The autocorrelation function is another means for detecting the periodic variation but not produced by Uster evenness tester. The autocorrelation functions for the data collected on the HSC for both yarn samples are shown in Figure 10. The lack of periodicity in the normal yarn samples is demonstrated by the low correlation value and without repeating pattern. The slub-yarn sample, on the other hand, has positive correlation peaks at lags of about 30 and 60 (with a relatively lower correlation value at the former) and those peaks appear repeatedly. There is also a negative correlation peak at a lag of ≈ 15 that repeats in intervals of about 30 lags. Since the yarn diameter readings considered in the calculations were collected at intervals of 8mm, it can be seen that the positive correlation peaks represent a repeated pattern in the yarn diameter at intervals of about 24 cm (for the peak at ≈ 30) and 48 cm (for the peak at ≈

60). Those intervals are in a close agreement to the values obtained from the spectrogram for the patterns of both; the long slub, and the whole slub repeat, respectively. Similarly, the negative correlation values correspond to distances of ≈ 14 cm can be attributed to the inter-slub distance where the repeat occurs at this interval between the high and the low diameters.

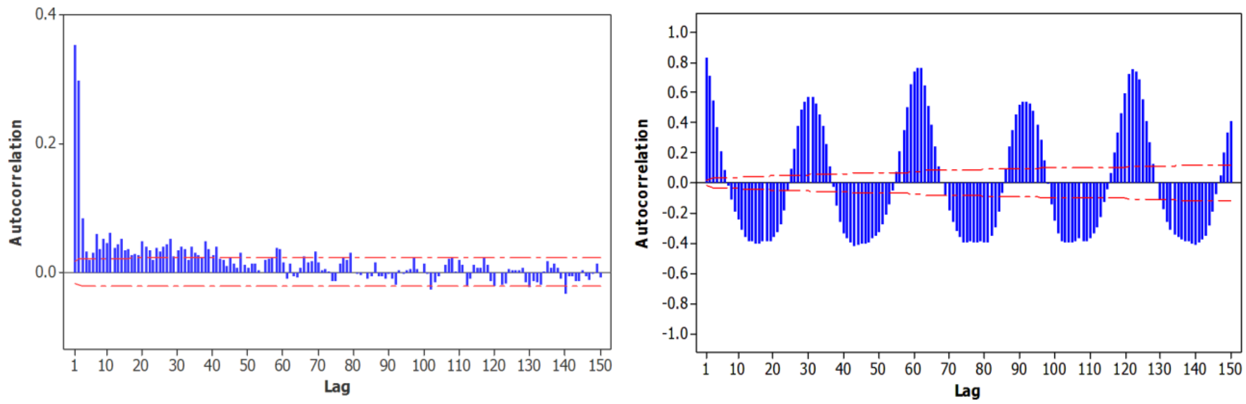


Figure 10. Autocorrelation function for yarn diameter measured at 8mm for the normal yarn (left) and the slub-yarn (right); with 5% significance limits indicated by the dotted line

4. Conclusion

The yarn diameter was analyzed using a computer vision system that utilizes a high speed camera. The images were processed using our developed robust technique that is relatively fast in removing the yarn hairiness and in filling the voids inside the yarn body. The data obtained from the applied algorithm were found to be significantly comparable to the commercial available instruments such as Uster evenness tester. The developed analysis was capable of detecting the short term, the long term, and the periodic variations of yarn diameter. To the best of the authors' knowledge, this work is the first to process the images of continuous long length of yarns to allow its time-series treatment. The newly developed processing algorithm demonstrated a fast and robust ability in treating the massive amount of yarn images compared to traditional edge detecting and processing methods. The robustness and flexibility of the suggested DiaLib® system opens the door for a relatively precise, cheap, and "transparent box" method for measuring the yarn diameter with a wealth of information that can be drawn during the analysis and may not be obtained from the commercial instruments.

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A dynamic and robust image processing based method for measuring the yarn diameter and its variation

Mohamed Eldessouki[1,2], Sayed Ibrahim[3] and Jiři Militky[1]

Abstract

The yarn diameter is an effective property in determining fabric structure and processing settings. There are different systems of measuring the yarn diameter; among them is the image analysis of the yarn's microscopic images. This method is considered to be more precise than other methods, but it is "static" in nature as it measures the property at scattered intervals and does not reflect the continuous variation of the yarn diameter. The goal of the current work is to measure the yarn diameter and its variation over a long length of yarn at fixed intervals to consider the "dynamic" change in the property. To achieve this goal, a high-speed camera (HSC) with a proper magnification was used to capture the images of the yarn and a new robust algorithm was developed to analyze the massive amount of yarn pictures in a reasonable time. The collected data for the yarn diameter were analyzed and compared to the results of the commercial Uster Evenness Tester IV. The results of the HSC were very comparable to the results of Uster and they were able to detect the short-term, the long-term, and the periodic variation of the yarn diameter.

Keywords

yarn diameter, robust image analysis, long-term variation, periodic variation

Yarn diameter is an important parameter that is used in all the calculations and modeling of fabric parameters[1] such as weave angle, yarn densities in warp and weft directions, yarn crimp ratio, cover ratio, fabric weight, and fabric volumetric density. The yarn diameter has also a direct impact on some of the measured fabric properties that affect the fabric dimensional and mechanical parameters.[2] Fabric performance and comfort depend on the yarn diameter as it correlates to the fabric air and water permeability. The settings of winding machines (e.g. cleaning knife) and most of the machines in the subsequent processes depend on the yarn diameter. On the other hand, the "exact" measurement of the yarn diameter is very difficult because of the inherent yarn unevenness and irregularity. That leads the textile specialists to talk about the yarn "size" or "count" instead of its "diameter". However, yarn count may not precisely indicate the yarn diameter, as two yarns with the same count may have two different diameters due to the changes in other parameters such as the fiber density and the yarn twist factor. Therefore, a good method of measuring the yarn diameter should maintain two basic features; it should measure the diameter with high precision and accuracy. It also should be able to determine the irregularities that occur in diameter at different bases (short- and long-term variations as well as the periodic variations).

The principles of measuring the yarn diameter can be classified[3] into four main categories that are

[1]Technical University of Liberec, Faculty of Textile Engineering, Materials Engineering Department, Liberec, Czech Republic
[2]Department of Textile Engineering, Faculty of Engineering, Mansoura University, Mansoura, Egypt
[3]Technical University of Liberec, Faculty of Textile Engineering, Textile Technology Department, Liberec, Czech Republic

Corresponding author:
Mohamed Eldessouki, Materials Engineering Department, Technical University of Liberec, Studentská 2, 461 17 Liberec 1, Liberec, Czech Republic.
Email: mohamed.eldessouki@tul.cz

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summarized with their pros and cons in Table 1. These methods are:

- The capacitive measurement: This is an indirect method of measuring the variation in yarn linear density (yarn count) which correlates to the yarn diameter through empirical relations from which the variation in yarn diameter can be calculated. The major drawback of this method is the indirect measurement of the yarn diameter (in fact, the mass variation is measured, not the diameter, but due to the high correlation between both parameters it is possible to measure one parameter and infer the other[4,5]). This method also depends on the testing environmental conditions because the capacitors are usually affected by the temperature and humidity. The resolution of this method is relatively low where the capacitors sample the data every 8 mm (e.g. old versions of the Uster tester).
- The optical measurement: This method is widely used[6] in commercial devices where high resolutions (e.g. 0.25 mm) can be obtained. This method determines the diameter after shedding a beam of laser light on the yarn and analyzing its projected image on a light sensor (Figure 1). The results of this method are highly dependent on the direction (the angle β) of the yarn as the projected image of the elliptical shape of the yarn may be larger or lower than the actual diameter. This method does not affect with the testing humidity or the fiber blend variation,[7] although it might be affected with the presence of lint and yarn hairiness. During these measuring methods, the yarn exists under a slight tension in the longitudinal direction which causes a compression in the transverse direction and may lead to changes in the measured diameter.
- The mechanical (electro-mechanical) measurement: In this method, the yarn runs between two sensors (fixed and freely moved) where the movement of the freely moved sensor is magnified for measuring the diameter. These sensors are implemented in different ways (cylinders, flat surface, etc.), among them a device similar to the tongue and groove mechanism used on drawing frames.[3] The yarn passes through the grove, and the tongue is attached to an arm that works as displacement amplifier to record the yarn diameter and its variations.
- The small scale microscopic measurement: This laboratory method is, principally, an optical method but it can be distinguished from the other optical methods by its small scale of measurements where the yarn diameter is measured in two directions; the cross section or the longitudinal view of the yarn.[8] The cross section of the yarn should be carefully cut at different positions and the diameter can be captured under the microscope with an appropriate magnification. Similarly, the yarn diameter is measured from the longitudinal projections of the yarn under the microscope at randomly different positions to account for the elliptical shape of the yarn.[9] Measurements can be done on the computer by a visual inspection or automatically using some image analysis techniques.

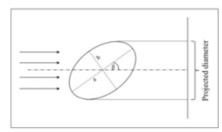

Figure 1. Schematic representation of the optical yarn diameter measurement system.

Table 1. Advantages and disadvantages of the methods for measuring yarn diameter

	Advantages	Disadvantages
Capacitive	– Works with the common yarn irregularity measurement systems – Primitive method	– Low resolution – Depends on the testing environment – Affected by other fiber properties (e.g. material type, fineness, specific density) and yarn parameters (e.g. twist, production technology)
Optical	– High resolution – Does not depend on testing environment – Simple and fast	– Measures the projected diameter not the real diameter – Yarn under tension reduces the measured diameter – Affected with the lint and hairiness
Mechanical	– Direct contact with the yarn	– Depends on the applied load during measurement
Small scale measurement	– Precise method - Measures the actual diameter	– Time consuming and tedious method – Not suitable for practical application in production scales

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The microscopic evaluation of yarn diameter is preferred for academicians in laboratories for its accuracy and it is used to calibrate the other methods. This method, however, is time consuming and needs many repeated samples, which makes it unsuitable for practical testing in production environments. It is also important to notice that the measurements of this method are "static" as they give information about the yarn at "scattered" points across the length of the yarn. This means; it does not capture the continuity of the variation in the measured property along the yarn and cannot usually detect the short-term, the long-term or the periodic variation of the yarn diameter.

This work aims at tackling the problems of the microscopic evaluation method and presents a new computer vision based system to measure the yarn diameter and its variation utilizing video processing and analysis algorithms. A high-speed camera (HSC) is used to capture the yarn images, and it was used to allow testing speeds comparable to speeds of the known commercial devices. A new image analysis algorithm is developed to enhance the captured images by eliminating the yarn hairiness and hence to obtain the yarn diameter. The continuity of the obtained results at fixed interval allows their treatment as a time series, which unveils some of the yarn characteristics that are produced from the commercial instruments. Two case studies are used in order to validate the presented system results; one of them is a regular ring-spun yarn and the other is a slub-yarn. Both yarns are tested simultaneously on the presented system and on the Uster Evenness Tester IV.

Experimental setup

Computer vision setup

Pre-investigation of the system and the analysis algorithm was initially performed using yarn samples evaluated under the optical microscope. An Olympus microscope was used with an automated stage to capture the yarn images along a certain distance with a magnification scale of 2.68 μm/pixel. The setup of the microscope is shown in Figure 2 with the motorized stage and the digital camera that is connected to the computer. The microscope system captures a longitudinal view of the yarn then the stage moves automatically with a predefined distance to capture another image. The obtained images were stitched and superimposed together to form a single picture of the whole yarn.

Because of the slow image acquisition with the automated microscope, alternative systems of acquisition were considered. A video camera with appropriate magnification lenses was applied; however, the yarn speed for this camera setup was about 15 m/min, which is less than the practical testing speeds of the commercial instruments. To run the yarns at 100 m/min (which is the testing speeds of other instruments such as Uster Evenness Tester IV), an HSC was used. The Olympus i-speed 3 HSC was installed with appropriate macro-lenses. The HSC captured yarn images with a speed of 150 frames per second (fps), the used shutter speed was 200×, and the resolution of individual frames in the recorded video was 1280 × 1024 pixels with a magnification scale of 10.2 μm/pixel. The yarn was lighted with a special Xenon lamp directed with an optical fiber to the HSC shooting zone. To avoid the effect of tension changes during the experiments, the yarn was running in front of the camera under constant tension using the tension compensation mechanism of Lawson Hemphill Constant Tension Transport (CTT) tester. The introduced computer vision system for measuring the yarn diameter (that includes the video camera setup with the analysis software) was assigned the name DiaLib®.

Tested samples

Two yarn samples were examined and analyzed using the suggested method and the results were verified against the measurements on the commercial Uster Evenness Tester IV. The first yarn sample is a normal ring-spun 100% cotton yarn with a count of 20 tex. The second yarn sample is a cotton slub-yarn produced by deliberately changing the draft on the spinning frame. The yarn count was 23 tex and the slub thickness was designed to be twice the yarn original diameter. The slubs were distributed across the yarn in two

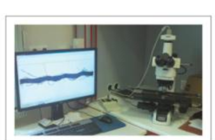

Figure 2. Microscopic setup with a motorized stage and CCD camera connected to the computer.

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populations with slub-lengths of 50 mm and 100 mm. The inter-slub separation distance was designed to be 150 mm. The yarn was tested on Uster Evenness Tester IV for its diameter and irregularity and the images of the yarn were captured using the high speed camera. The yarn speed during testing on the Uster and the HSC was 100 m/min.

Methods

Image processing and analysis

The longitudinal view of the yarn sample was acquired with a proper magnification using a digital camera connected to the computer. The acquired images were converted to binary with a suitable threshold to allow faster processing. The yarn diameter is calculated by counting the pixels belonging to the yarn body at specified intervals. The existence of yarn hairiness with protruding fibers does not allow the direct and automatic finding of the yarn limits (where the diameter can be measured) because those protruding fibers will be outside the actual diameter. Therefore, the automatic measurement of the yarn diameter is faced with three obstacles; firstly, the exclusion of the yarn hairiness from the yarn body. Secondly, the filling of the voids inside the yarn body that occur during the conversion to binary images (due to the shading differences in the microscope images). Thirdly, the standard algorithms for edge detection (to remove the hairiness) and object filling (to remove the voids) are relatively slow and there is a need to increase the speed of the processing algorithm. These obstacles will be folded many times in accordance with the interval distance between the measurements and the number of the images to be processed. For example, there is about 350 slices in an image of a yarn with length ≈7 cm and interval between readings of 0.2 mm, and this number reaches many thousands for longer yarn samples.

To face these challenges, a new algorithm was developed to be robust with the increase in number of pictures and sampling points. To find the yarn body in an image (let us call it I1), two other images of the yarn were created by translating the yarn image in the vertical direction with distances $\pm\delta$ (let us call the created shifted images I2 and I3). Then, the three images are added together and the summation matrix is logically compared to a certain threshold to produce a binary image with filled yarn body and trimmed of the majority of yarn hairiness.

To demonstrate the algorithm, an example is shown in Figure 3 with a small scale matrix with a height of 20 pixels (while actual yarn images have a height of 1024 pixels). The example in Figure 3 shows one vector (a column that can be called C1) that represents what is extracted from the binary matrix of the yarn

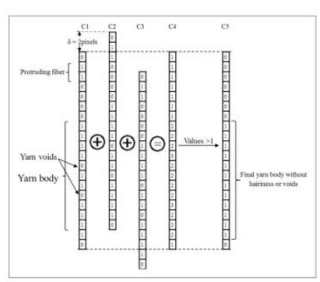

Figure 3. Example of the suggested algorithm to remove hairiness and fill-in yarn voids to find yarn body and diameter.

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image at a certain cutting interval, and the same calculations can be extended for all intervals in the yarn image. The example shown in Figure 3 represents the black background with zeroes and the white elements of the yarn with ones. The representation vector C1 corresponds to a slice of the image where the yarn body is represented with a series of ones (including some voids of zeroes) and a part of the protruding fiber at the top of the vector. This vector was shifted upward with a distance (δ) of 2 pixels (which resulted in another vector that can be called C2) and shifted downward with the same δ (to result in a third vector C3). The vector C4 is the summation of C1, C2 and C3; then it is logically compared to consider the positions with numbers less than or equal to one as background (substituting a value of zero at these positions) and the positions of values greater than one to be foreground (substituting a value of one). The resulted vector C5 shows the solid yarn body without voids or yarn hairiness from the protruding fibers.

To compare the suggested algorithm with "traditional" edge detection techniques, it is important to understand how these techniques work. Traditional edge detection techniques generally depend on converting the image from its spatial domain into a frequency domain to apply some filters on the image and then the image is converted back to its spatial domain. After this process, the detection algorithm applies some programming loops to determine the yarn boundaries and remove the hairiness. These traditional methods are computationally expensive and depend on the available hardware resources in completing these tasks. Our suggested method, however, analyzes pictures in their spatial domain only and avoids the loops that consume the computer resources. As the time for any image processing method depends on the used algorithm and the available hardware resources, the suggested system used a personal computer with an Intel Core i3 processor to analyze ≈10,000 pictures in ≈8 min.

Although this algorithm is relatively fast and robust compared to the standard edge detection and image filling algorithms, it has some drawbacks and errors that may occur during the processing. These errors result from the dependency of the algorithm on the deliberate choice of the image shifting (δ) and on the position of the protruding fibers and voids (which are random). After considering different values for the image shifting (δ) and its effect on the calculation accuracy, it was found that a δ value is approximately equal to the thickness of the protruding fiber is a good choice in most cases. Therefore, the value of δ is calculated during the analysis based on the magnification scale and the fiber's average diameter that are given by the user. To illustrate the errors that may occur, Figure 4

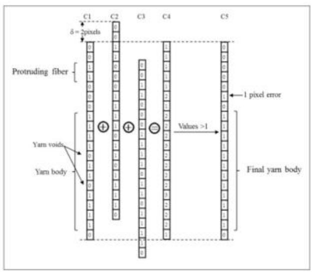

Figure 4. Example of the suggested algorithm with an error in the hairiness removal.

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shows a vector from the yarn image similar to the one shown in Figure 3 with a minor change in the position of the protruding fiber which resulted in an error as indicated in C5 by considering one extra pixel as part of the yarn body. A similar error can occur for consecutive voids with a close proximity. Considering the image scale (where one pixel is about 2.6 μm for the microscopic images to 10 μm for the camera images) and the averaging of the thousands of readings to calculate the yarn diameter, the calculation error of this algorithm can be found in the order of 10^{-6} mm per pixel. This error order is relatively small and does not significantly affect the final results of yarn diameter.

Data analysis and parameterization

The data obtained from the analysis of the HSC images are taken at regular intervals (space and time intervals), which allow the data to be treated as time series. Beside the normal statistics that can be derived for any set of data, the discussion here will focus on the parameters that depend on the data continuity to demonstrate the advantages of the introduced procedure (with the dynamic measurement of the yarn) over the static procedures.

The length-variance curve. The length-variance curve (LVC) determines the relationship between the variability of the yarn diameter and the measurement intervals. The variability (CB) is expressed as the coefficient of variation and can be measured at a certain yarn cut length (λ) according to Ma and Korobov:[10]

$$CB(\lambda) = \frac{s(\lambda)}{\bar{x}(\lambda)} \tag{1}$$

where, $s(\lambda)$ denotes the standard deviation of yarn diameter and $\bar{x}(\lambda)$ is the average value at a given cut length λ. The "cut length" represents the distance between two consecutive diameter readings on the measurement system and these calculations are repeated at different cut lengths to construct the LVC.

Deviation rate. The deviation rate (DR) measures the frequency (the rate of occurrence) for a diameter value to deviate from the yarn mean diameter plus or minus a certain sensitivity limit (α). For the deviation rate calculation, the function $p(n, \alpha)$ should be calculated to allow the frequency calculation. This function can be defined as:[11,12]

$$p(n,\alpha) = \begin{cases} 1 & f(x_n) \geq (1+\alpha)\bar{\mu} \\ 0 & (1-\alpha)\bar{\mu} < f(x_n) < (1+\alpha)\bar{\mu} \\ 1 & (1-\alpha)\bar{\mu} \geq f(x_n) \end{cases} \tag{2}$$

The deviation rate can be calculated from the function $p(n, \alpha)$ according to the relation:

$$DR_\alpha[\%] = \frac{\sum_{n=1}^{N} p(n,\alpha)}{N} * 100 \tag{3}$$

where n is an index, α is the sensitivity limit, $f(x_n)$ is the diameter value, $\bar{\mu}$ is the mean diameter of the yarn sample and N is the total number of readings.

Absolute mean deviation. The absolute mean deviation ($U\%$) is a commonly used term to define the mass irregularity of yarns and can be used to define the irregularity in diameter as well. It can be calculated for a series of diameter readings (x_n) using the relation:

$$U[\%] = \frac{\sum_{n=1}^{N} |x_n - \bar{\mu}|}{N * \bar{\mu}} * 100 \tag{4}$$

Integral deviation rate. The integral deviation rate (IDR) accounts for the diameter's absolute mean deviation at certain sensitivity limit (α) and it can be considered as a generalization formula for the $U\%$ (where $U\% = \text{IDR}$ at $\alpha = 0$). The starting function for the IDR calculation is the function $y(n)$, similar to the frequency function $p(n, \alpha)$, where:

$$y(n,\alpha) = \begin{cases} |f(x_n) - (1+\alpha)\bar{\mu}| & f(x_n) \geq (1+\alpha)\bar{\mu} \\ 0 & (1-\alpha)\bar{\mu} < f(x_n) < (1+\alpha)\bar{\mu} \\ |f(x_n) - (1-\alpha)\bar{\mu}| & (1-\alpha)\bar{\mu} \geq f(x_n) \end{cases} \tag{5}$$

Then, the IDR can be calculated according to:

$$IDR_\alpha[\%] = \frac{\sum_{n=1}^{N} y(n,\alpha)}{N * \bar{\mu}} * 100 \tag{6}$$

Autocorrelation function. Autocorrelation is an expression for the correlation of a time series with its own past and future values. The autocorrelation function (ACF) that measures the correlation of a data series $x(n)$ with itself shifted by some delay (lag) m can be calculated from the auto-covariance function:[13]

$$C(m) = \frac{1}{N-m} \sum_{n=1}^{N-m} (x(n) - \bar{\mu}) \cdot (x(n+m) - \bar{\mu}) \tag{7}$$

And the sample auto-correlation function at the lag m can be calculated as:

$$\rho(m) = \frac{C(m)}{C(0)}, \quad m = 1, 2, 3, \ldots, M < N \tag{8}$$

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Results and discussion

It is worthy at the beginning of the discussion to clarify four points regarding the suggested algorithm and the selected yarn samples. First, the proposed method as well as all methods that measure the diameter with a single yarn projection (i.e. using only one camera or sensor) work under the basic assumption that: during the measurement of longer lengths of yarn, the yarn rotates around its axis and the huge amount of collected readings will eventually account for the elliptical shape of the yarn. Second, the choice of the slub-yarn as a second case study versus the normal ring-spun yarn is based on the continuous and periodic variation of yarn diameter in these yarns which should clarify the performance of the proposed system in measuring the yarn diameter and detecting the different types of its variation.

Third, the results of the HSC tested yarns were compared to the Uster Evenness Tester IV although the most recent version of the Uster Tester V has a special configuration for measuring the slub-yarns and gives more detailed and relatively precise information about the special structure of these fancy yarns. This study, however, was intended to verify the validity of the applied algorithm even if it does not compete with the advanced hardware and software implemented by Uster. Fourth, the Uster Tester is the most used instrument in industry and is able to deal with the measurement as a function of time and results in useful information such as LVC, spectrographic data, and so on. On the other hand, the suggested algorithm is a relatively cheap and "transparent box" system that enables us to verify the results obtained from Uster and other instruments that work on the optical principle. Also, the suggested algorithm allows functions and parameters that are not produced by commercial instruments to be calculated (e.g. autocorrelation function, fractal dimensions, etc.) and these parameters are out the scope of the current study.

Microscopic images

The yarn samples were tested on the microscope setup where the individual captured frames represent a length of about 2.9 mm of the yarn length. The microscope software applies a picture stitching algorithm (for a collection of about 25 pictures) that considers the overlapping of the pictures to create a single image (of about 7 cm) as shown in Figure 5(a). The operation was repeated for a total sample length of 3 m. The individual pictures (for the 7 cm) were processed and an example for a magnified part of the yarn is shown in Figure 5(b). The yarn diameter can be calculated at any required reading interval where the minimum interval is about 2.68 μm (that is equivalent to 1 pixel). A yarn image that was processed at an interval of 0.2 mm is shown as a superimposed image of the actual yarn and the detected boundaries in Figure 5(c) where the white parts of the vertical lines represent the detected yarn boundaries at each interval. It can be seen in the processed image that the automated algorithm was capable of detecting the yarn boundaries and considering the yarn body despite of the differences in the gray levels inside the yarn. The method, however, failed to remove the whole protruding fiber as circled in Figure 5(c) (the first reading to the right). The reason for the system to consider this hairiness inside the yarn diameter is, partially, because of its close proximity to the yarn body and its positioning in a vertical way (which resulted in more pixels in the cross-section compared to the positioning of horizontal fibers). After all, the method was able to remove about half of the circled protruding fiber

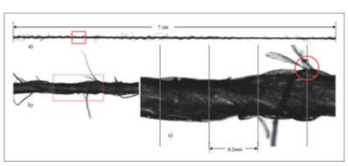

Figure 5. (a) Longitudinal view of the yarn as captured under the microscope; (b) the magnification of the window drawn in (a); (c) a magnification of the window drawn in (b) with illustration of the diameter measuring intervals.

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and the remaining part is much less than 10% of the yarn diameter which makes this error almost negligible after averaging the thousands of reading.

The high speed camera

A 100 m of the each yarn sample (a one minute run) was recorded and the sampling of the yarn diameter from the video was flexible to be adjusted at any interval (with a minimum distance of about 0.01 mm between diameter readings). To compare the HSC with the Uster Tester results, the measurement interval was adjusted to 0.3 mm to match the interval used in Uster measurements. Two sets of data produced from the HSC with a set of measurement at 0.3 mm and another set of readings that were averaged every 8 mm to match the results produced by Uster Tester. Once the videos were processed and the results from HSC were collected, the analysis was performed to produce the statistical and spectral features of the yarn diameter. We should point out that the Uster Tester uses two perpendicular cameras to measure the yarn diameter and reports two results; the one obtained from the two cameras and the other from values measured using one camera.

Basic statistics and short-term variation. The results of both the Uster Tester and the HSC are summarized in Table 2 at the two measurement intervals 0.3 mm and 8 mm for both yarn samples. The average yarn diameter for both yarn samples is comparable when measured using Uster and obtained from the suggested method. The variability of values, on the other hand, as expressed in terms of the coefficient of variation (CV) is slightly different especially as measured at short intervals of 0.3 mm. It is also observed that the CV values are generally higher at short measurement intervals; that is expected as more variability is encountered at these lengths. This increase is also in agreement with the behavior of the length variation curve where higher variation is usually found at shorter measuring lengths. Although the slub-yarn has two different diameters as can be clearly seen in the bimodal histograms of Figure 6, the results of Uster report a single value for the diameter (with a high variation) which is the mean of all values if considered as a normal distribution. The diameters calculated from the high speed camera are also shown in Figure 6 with a bimodal histogram for the slub-yarn sample. The theoretical normal distribution curves calculated from the HSC analysis are shown in the figure with mean values relatively close to the data obtained from Uster. The availability of the raw data from the HSC allows the analysis of the two averages of the bimodal distribution for the slub-yarn. The Hartigan's DIP method[14,15] was used for testing the unimodality and the finite mixture distributions method[16-18] was applied to separate the bimodal curve. Analysis of the bimodal distribution indicates that the first mode is 0.301 mm (standard deviation 0.066 mm) and the second mode is 0.192 mm (standard deviation 0.024 mm).

Long-term variation. The long-term variation in the yarn diameter can be detected using the LVC. The application of the image processing allows the determination of the yarn diameter at different intervals, which permitted the construction of the LVC. The LVC for the tested yarns are shown in Figure 7 as produced from the applied algorithm and compared to the curve obtained from Uster Evenness Tester. The theoretical LVC for an ideal yarn can be represented by an inclined straight line (on a diagram with double logarithmic scale) and any deviation from the ideal line corresponds to a long-term variation. It can be seen from the figure that the results of the HSC are very comparable to the results of the Uster Tester and the LVC curve for the normal yarn is almost straight while being curved for the slub-yarn. The LVC is very useful in comparing the

Table 2. Uster and HSC diameter results for the tested yarn samples

		Uster		HSC	
		0.3 mm	8 mm	0.3 mm	8 mm
Normal yarn	Average diameter (mm)	0.22	0.218 (2D[a])	0.235	0.235
	CV (%)	18.68 (2D) 19.82 (1D[b])	13.40 (2D)	23.34	13.53
Slub-yarn	Average diameter (mm)	0.26	0.259 (2D[a])	0.239	0.24
	CV (%)	33.47 (2D) 34.01 (1D[b])	31.58 (2D)	36.86	30.33

[a]Values measured using two perpendicular cameras.
[b]Values measured using one camera.

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regularity of different yarns and the similarity between the curves produced from Uster and from the HSC is an evident for the validity of using this method in the yarn diameter measurement for long lengths.

The deviation rate percentage refers to the cumulative yarn length with diameters above or below a certain limit defined as a percentage of total sample length.[19] For example, if 30% is the calculated *DR* at

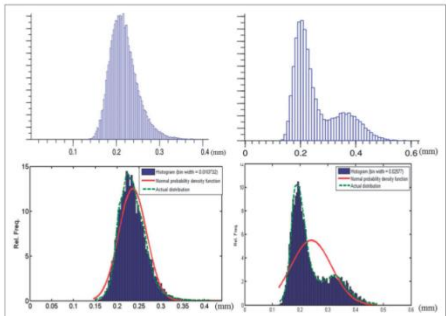

Figure 6. Histogram for the yarn diameter measured by Uster (*top*) and produced from the analysis of HSC (*bottom*) for the normal yarn (*left*) and the slub-yarn (*right*).

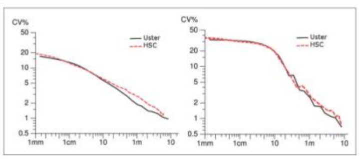

Figure 7. LVC for the yarn diameter measured by Uster and produced from the developed HSC analysis for the normal yarn (*left*) and the slub-yarn (*right*).

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$\alpha = 10\%$ for a yarn with average diameter d, it means that 30% of the total tested length has a diameter bigger than $1.1\,d$ or smaller than $0.9\,d$. The deviation rate measured by Uster is illustrated in Figure 8 as well as the values calculated from the HSC. The curves were calculated at different measurement lengths where the *DR%* was calculated at the original interval of 0.3 mm and was smoothed for lengths $\lambda = 1.5$, 3, and 10 m of the yarn samples. By smoothing we mean the averaging of the data and consider one reading for each length λ. For example, at $\lambda = 1.5$ m an average for 5000 readings from the readings with $\lambda = 0.3$ mm were considered as one reading in the subsequent calculations. The curves shown in Figure 8 for the HSC were calculated as α changes in the interval [−40:100] and demonstrated for the slub-yarn in the interval [−30:50] for illustration purposes. The general trend of the calculated curves is similar to those produced by Uster, although slight differences in numbers are found and can be attributed to the differences of the individual readings. The IDR is also shown in Figure 8 with a similar trend, albeit the calculated IDR% at $\alpha = 0$ for the different curves are more separated than the same values of DR at the same level of α.

Periodic variations. The periodic variations can be detected using the spectrogram. Although spectrograms are "commonly" used to demonstrate the mass periodic variability, the Uster Tester also "optionally" produces a similar spectrogram for the diameter variability. The rules applied in explaining the mass spectrogram are similarly used in explaining the diameter spectrogram. The yarn diameter spectrograms which are illustrated in Figure 9 as obtained from the Uster Tester for both yarn samples. The spectrograms produced from the data obtained from the HSC image analysis are shown also in Figure 9, which indicates a relatively high similarity with the fault peaks detected by Uster for the slub-yarn sample, while no similarity can be detected for the normal yarn. The contrast between the HSC calculated spectrograms for both samples is very indicative of the existence of periodicity along the

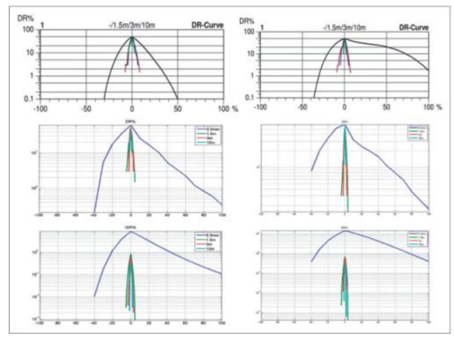

Figure 8. The DR% (*middle*) and the IDR% (*bottom*) of yarn diameter as calculated from the HSC algorithm and compared to the DR% obtained from Uster (*top*) for the normal yarn (*left*) and the slub-yarn (*right*).

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yarn samples. For the slub-yarn, where periodic variation exists, the HSC's spectrogram has dominant peaks that match the ones obtained from Uster, while in the normal yarn, with little periodic variation, the calculated spectrogram does not have such dominant peaks. The peaks shown on the HSC's spectrogram for the normal yarn are illusive, as the vertical scale of the curve is very small compared to the slub-yarn's calculated curve. The four dominant peaks on the spectrogram produced from the HSC for the slub-yarn sample are located at about 0.07, 0.13, 0.25 and 0.42 m, which can be found on the Uster spectrogram at the same wavelengths. The peak at the wavelength around 7.5 cm can be attributed to mechanical faults and drafting waves and the peak that is located around 13 cm can be attributed to the inter-slub distance and the peak around 25 cm can be attributed to the pattern of the long slub (10 cm) plus its inter-slub distance (15 cm). The peak at 45 cm can be attributed to the whole repeat for the pattern of the two slub populations (that is 5 + 15 + 10 + 15 cm).

The autocorrelation function is another means for detecting the periodic variation but not produced by the Uster Evenness Tester. The autocorrelation functions for the data collected on the HSC for both yarn samples are shown in Figure 10. The lack of periodicity

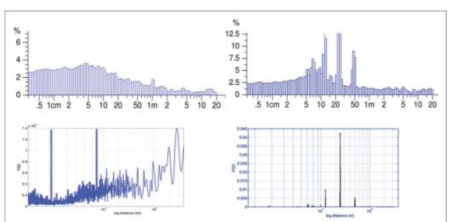

Figure 9. Spectrogram for the yarn diameter measured by Uster (*top*) and produced from the developed analysis (*bottom*) for the normal yarn (*left*) and the slub-yarn (*right*).

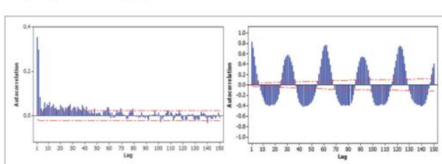

Figure 10. Autocorrelation function for yarn diameter measured at 8 mm for the normal yarn (*left*) and the slub-yarn (*right*); with 5% significance limits indicated by the dotted line.

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in the normal yarn samples is demonstrated by the low correlation value and without repeating pattern. The slub-yarn sample, on the other hand, has positive correlation peaks at lags of about 30 and 60 (with a relatively lower correlation value at the former) and those peaks appear repeatedly. There is also a negative correlation peak at a lag of ≈ 15 that repeats in intervals of about 30 lags. Since the yarn diameter readings considered in the calculations were collected at intervals of 8 mm, it can be seen that the positive correlation peaks represent a repeated pattern in the yarn diameter at intervals of about 24 cm (for the peak at ≈ 30) and 48 cm (for the peak at ≈ 60). Those intervals are in a close agreement with the values obtained from the spectrogram for the patterns of both; the long slub, and the whole slub repeat, respectively. Similarly, the negative correlation values corresponding to distances of ≈ 14 cm can be attributed to the inter-slub distance where the repeat occurs at this interval between the high and the low diameters.

Conclusion

The yarn diameter was analyzed using a computer vision system that utilizes an HSC. The images were processed using our developed robust technique that is relatively fast in removing the yarn hairiness and in filling the voids inside the yarn body. The data obtained from the applied algorithm were found to be significantly comparable to the commercial available instruments such as the Uster Evenness Tester. The developed analysis was capable of detecting the short-term, the long-term, and the periodic variations of yarn diameter. To the best of the authors' knowledge, this work is the first to process the images of continuous long-length of yarns to allow its time-series treatment. The newly developed processing algorithm demonstrated a fast and robust ability in treating the massive amount of yarn images compared to traditional edge detecting and processing methods. The robustness and flexibility of the suggested DiaLib® system opens the door for a relatively precise, cheap, and "transparent box" method for measuring the yarn diameter with a wealth of information that can be drawn during the analysis and may not be obtained from the commercial instruments.

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