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Image segmentation based determination of elastane core yarn diameter

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Image Segmentation Based Determination of Elastane Core Yarn Diameter

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Abstract
Yarn diameter is one of the key knitted fabric parameters, whose accurate determination, however, continues to be a difficult task. The goal of the study presented was to calculate the diameter of dry and wet relaxed yarns with and without incorporated elastane using image-processing and -analysis tools implemented in MATLAB. Compared to the images of wet relaxed samples, a much more sophisticated segmentation approach had to be implemented for dry relaxed yarn images due to their weaker yarn-background contrast. The values calculated were compared with those obtained with the conventional yarn thickness determination method developed by Sadikov. Linear correlation between the two techniques was found to be substantial – coefficients of determination for the yarn diameters of the wet and dry relaxed samples were 0.87 and 0.72, respectively. Unlike Sadikov's method, our newly developed technique calculates yarn core diameter without hairiness.

Key words: *elastane core yarn, image analysis, image segmentation, yarn diameter.*

Introduction

Yarn diameter is an important knitted fabric parameter, but it is far from trivial to determine it accurately. A yarn is not a solid body with a uniform and known density; it is characterised by a significant amount of air – its porosity may range from 30 to 70% – and considerable variability in thickness both within each yarn as well as between yarns. The core of a yarn is compact, while its sheath consists of free fibre ends protruding from the yarn outwards [1, 2]. This feature, known as hairiness, is a very important yarn characteristic influencing the production process and fabric properties. Another issue to consider is yarn's compressibility and the related question whether to measure its diameter in a non-compressed or compressed state. Generally speaking, the factors affecting yarn diameter belong to one of the following three groups: fibre properties, yarn properties, and production process and spinning technique characteristics [3].

There are many methods available for measuring or calculating yarn diameter. These techniques have undergone considerable changes and development over the years; nevertheless, none of them has been accepted as a standard method. They can typically be classified as (a) methods based on measuring yarn mass and length, (b) optical or (c) mechanical methods [4].

The study presented is focused on the implementation of an optical method based on image processing and image analysis algorithms. The research objective was to assess the applicability of a computer supported image processing approach for determining the diameter of dry and wet relaxed yarns with and without incorporated elastane, respectively. The yarns with an incorporated elastane core, particularly those wet relaxed, exhibit strong bulkiness and crimp. These features make precise yarn diameter measurements difficult, especially when the methods are based on a subjective determination of the yarn boundaries. The method presented enables accurate and objective yarn boundary detection and, consequently, the calculation of yarn diameter. Furthermore previous research work on this topic was mainly focused on conventional yarns without elastane. No detailed study has specifically addressed the problem of determining elasticised yarn diameter. The images of dry relaxed yarn samples were of very poor contrast, making their segmentation and subsequent analysis a challenging task. The diameter values calculated were compared with those obtained with the conventional yarn thickness determination method developed by Sadikov [5].

Overview of past research

Accurate image segmentation – a partitioning of a digital image into its constituent regions or objects – is one of the most difficult tasks in many machine vision and image processing applications [6]. One of the techniques frequently applied to perform segmentation has been image thresholding, which is based on the differences between the intensities or colours in the foreground and background regions of an image [7]. Many of the past studies dealing with yarn diameter determination include global or adaptive thresholding schemes.

Fletcher and Roberts performed computer assisted yarn determination studies already in the 1950's and 1960's [8, 9], in which they measured the minimum and maximum diameter of a yarn directly using the camera lucida. The number of measurements was twenty in the first studies and was later increased to fifty.

Sirang *et al.* [10] measured the yarn diameter with a microscope at a magnification of 100×. The yarn diameter projected on the screen was determined by measuring the distance between yarn boundaries. Five bobbins were examined for each yarn and thirty measurements taken from each bobbin. The coefficient of variation was relatively high, i.e. 13 – 15%.

Cybulska [11] used the system developed at the Institute of Mechanical Technology of Textiles at the Technical University of Lodz, Poland. A microscopic image of yarn registered by a camera was processed and analysed by means of a computer. The yarn was divided into two basic elements: yarn core and hairiness. The core was defined as a part of the yarn that formed a compact agglomeration of fibres, while the rest of the yarn, consisting of single outlaying fibres or their agglomeration, constituted hairiness. The yarn thickness at any point of the yarn length was defined as the local diameter of its core. The method for determining the edge of the core consisted of applying an image segmentation step, followed by the correction of edges previously determined.

Basu *et al.* [12] assessed the yarn diameter and twist angle of various rotor-spun and ring-spun yarns with the image analysis technique. An Instron Tensile Tester was used for the uniform tension of yarn samples to remove the crimp from the yarn. The loaded yarns were fixed onto a glass slide and mounted on a microscope for yarn diameter analysis. Using an Olympus BX50 microscope at 40× magnification and a CCD camera, the yarn samples were illuminated under transmitted light, where the CCD solid image sensor provided a high-resolution image. The images were analysed with Image-pro-Plus 4.0 software. The same as with Cybulska's approach, the yarn was divided into the yarn core and hairiness. The edges of the yarn were determined to be able to define the yarn thickness as the local diameter of the core. 200 readings were taken for each yarn sample to keep the percentage accuracy level within 2 – 3%. The coefficient of variation was 11 – 15%.

Kilic and Okur [13] studied the relationship between the yarn diameter, yarn diameter variation and yarn strength. In their study, 100% cotton combed ring-spun and 100% wool worsted yarns of different yarn linear densities and treated with different twist factors were investigated. Yarn diameters were measured with a Gaertner M-1170 Micrometer Slide Comparator at 0.001 accuracy and 32× magnification. A mechanism consisting of a yarn creel, yarn guides and yarn tensioners was used for measuring the yarn diameter under constant tension (22 ± 1 cN) for all yarn types.

Zhang *et al*. [14] presented a new method of automatic yarn linear density recognition based on the processing of a digital image of yarns within the woven structure. Digital images of the yarns were acquired using a scanner. In order to eliminate the influence of the hairiness of yarns and improve measurement precision, the Fuzzy C-Means Clustering algorithm (FCM) was proposed. The ratio between the yarns and interstice between yarns within the woven structure was obtained. In the research, 100% cotton yarns with 28 tex linear density were analysed.

Jaouadi *et al.* [15] studied the effect of the yarn and fibre properties on the yarn packing fraction. They described the development of an experimental device enabling determination of the real yarn diameter. The real diameter was defined as the measurement of the yarn dimension without air. The device consisted of a twist tester, camera and computer with image processing software. A tension of 1 cN/tex was applied to the yarn sample according to the French standard FN G07-079 for the removal of crimp. A 500 mm test length of yarn was subjected to an increase in twist (a step of 50 turns). For each twist step, one microscopic (40× magnification) yarn photo was captured and analysed using Image Pro-Plus 2.0 software. The yarn diameter was determined by measuring the edges of the yarn core. The mean diameter was calculated from 100 readings.

Rameshkumar *et al.* [16] studied geometrical, mechanical, quality and comfort characteristics of core-spun polyester/silk yarns in comparison to 100% polyester and 100% silk yarns. They assessed the yarn diameters using a Leica projection microscope. For each yarn, the diameters were measured randomly at 100 locations. The coefficient of variation ranged considerably (4 – 27%).

Carvalho *et al.* [17] focused on the determination of the statistical correlation between yarn diameter and yarn linear density. The experimental methods were based on optical analysis and on the image processing techniques applied to electron microscope images. Several different cotton yarns over a wide range of linear densities were examined. The results showed that the typical theoretical values of the yarn porosity factor presented in literature were more than 60% lower than their experimental findings.

In another research, Caravalho *et al.* [18] developed an original system to measure yarn diameter using a coherent optical signal process to eliminate the influence of hairiness over the output signal. The system consisted of optical hardware to produce an image used to characterise the yarn diameter, as well as electronic hardware that converted the optical yarn diameter image into the corresponding voltage. LabVIEW software was used to acquire and process the output voltage interfaced through a Data Acquisition Board. Three 100% cotton yarns with different linear densities (49.17 tex, 62 tex and 295 tex) were analysed. The methodology presented was shown to generate reliable yarn diameter variation results.

Unal *et al.* [19] investigated the spliced yarn diameter retained with regard to splicing parameters as well as fibre and yarn properties. Diameter measurements of the parent and spliced ring spun yarns were performed with the yarn measurement modulus of a Constant Tension Tester (CTT). In the CTT device, the tester was computer aided, which enabled the user to take snapshots of the yarn profile. The yarn diameter was measured optically while the yarn was passing between an optical sensing head and light source. The optical head had light receiving elements, with each one being equivalent to a pixel. Light was projected on one side of the yarn and was either blocked by the yarn or received by a pixel in the optical head array. The computer calculated the yarn diameter as the distance between the first and last dark pixel. Test speed was adjusted to 50 m/min. The threshold value of the 8-bit grayscale image was set to 50 in order to capture an image of the yarn core only and avoid surface hairiness. The default length measurement was 100 m. Conventional ring-spun cotton yarns were investigated.

Behtaj *et al.* [20] developed a novel objective yarn bulk measurement method based on the image analysis technique. Two orthogonal images of hard polyester air-jet textured yarns were taken from the same part of yarn and then transformed into grayscale ones. Each grayscale image was further processed separately by extracting the yarn image from the background using adaptive thresholding. The binary image obtained was then used as an input for the second part of the algorithm to measure yarn volume. The long rare loops, considered as noise, were deleted with morphological filtering. The width of two orthogonal images was measured pixel by pixel along the yarn. Finally the total volume of the yarn was obtained by integrating the volume of all individual imaginary ovals with their two diameters replaced by the two widths of orthogonal images at the corresponding pixel.

Majumdar *et al.* [21] examined the properties of ring-spun yarns made from cotton and regenerated bamboo fibres. The yarn samples were tested for their diameter using a Projectina microscope. For each sample, five cones were selected randomly, and from each one 10 readings of the diameter were recorded. The mean diameter was calculated from 50 individual readings. Based on the yarn linear density and diameter, the packaging fraction of the yarns was calculated as well. The results were additionally commented on based on SEM images.

Yuvaraj and Nayar [22] developed a simple technique for measuring yarn hairiness, based on image processing, that was not affected by the air drag and hair bending occurring when the material was passed over the guides and tensioners during the testing. Two grounded plates were placed in the position between the positively charged electrodes above and below the yarn. After electrical voltage was applied, the charged protruding fibres were attracted towards the ground plate and stood up from the yarn surface. Images were captured with a Sony 7.2MP Cybershot camera in the VGA mode. Hairiness data were acquired in a four-stage process, and the authors compared the findings with those obtained from commercial testers. The results correlated well with those obtained with a Zweigle hairiness meter.

Shady *et al.* [23] developed a digital image processing approach to evaluate woven fabric structure parameters utilising a Wiener filter to decompose the fabric image into two sub-images, each of which belonged to either a warp yarn or weft yarn group. The sub-images were further analysed to outline the yarn boundaries and, hence, characterise fabric surface parameters, including the yarn diameter. Three 100% cotton fabrics in plain, twill and satin were selected for this study and each fabric structure was represented by two warp/weft densities. Five different images were captured by a CCD camera equipped with a zoom lens attached, and digitised for each sample type. All images were processed using histogram equalisation to reassign the brightness to improve the visual appearance. The image processing technique presented is applicable to analyse uni-color fabrics, while it is not suitable for fabrics with an extreme difference in the colours of warp and weft yarns.

Rukuižiene and Kumpikaite [24] investigated initial warp tension and weave influence on diameter projections of warp yarns. The diameters of warp yarns within fabrics woven with different initial tensions were measured with a Askania microscope and Metric program. The warp diameters were measured at ten different locations under 10× optical magnification. For the woven fabric, half wool yarns (45% wool, 55% PES) with a linear density of 18 tex × 2 were used.

Krupincova *et al.* [25] focused their research on the image analysis of yarn diameters within cross-sections of 100% cotton, 100% PP and 50% Co/50% PP woven structures in plain weave. Lateral yarn deformations were assessed from the cross-sections of real fabrics, from yarn flattening caused by compression and bending at a 0.07, 0.26 and 0.44 N loading force, and from yarn compression between two parallel plates at deforming forces of 10, 15, 20, 25, 30 and 40 N. Fabric cross-sections were prepared with a blend of bee wax and paraffin as a fixing medium.

Zhong et al [26] proposed a yarn diameter unevenness evaluation method based on measuring the diameters of a series of testing points contained in the image sequence captured from a moving yarn. A computer-based yarn dynamic image acquisition and processing system was designed which combines yarn dynamic image acquisition, image processing, diameter measurement and unevenness analysis together. In the experiment, 18 tex cotton knitting yarns produced by different manufacturers were used. The yarn detection speed was 20 m/min, yarn tension 0.18 N and the effective testing length of yarn was 100 m. The interval distance between two neighbouring testing points was 5 cm. Through the comparison of the test results obtained from the Uster instrument, a correlation between the new method and Uster method proved that the new one can be used to evaluate the unevenness of the yarn diameter.

Materials and methods

Yarns

Our experiments were carefully planned and yarn samples were specifically made for the research to be able to compare non-elasticized yarns to elasticised ones. Yarns were spun from two types of staple fibres, i.e. viscose (CV) and polyacrylonitrile (PAN) in order to investigate materials of different origins (natural polymer vs. synthesised polymer) and diverse properties: specific gravity, dimensional stability in wet processing and mechanical properties. From each raw material, elastomeric yarns with the same linear density (100 tex) were made to order with three different spinning/twisting processes: mouliné twisted yarn (composed of elastomeric core-spun yarn and yarn without elastane, both ring-spun), core-twisted yarn (elastane filament yarn, core-twisted with two ring-spun yarns) and core-spun yarn (yarn

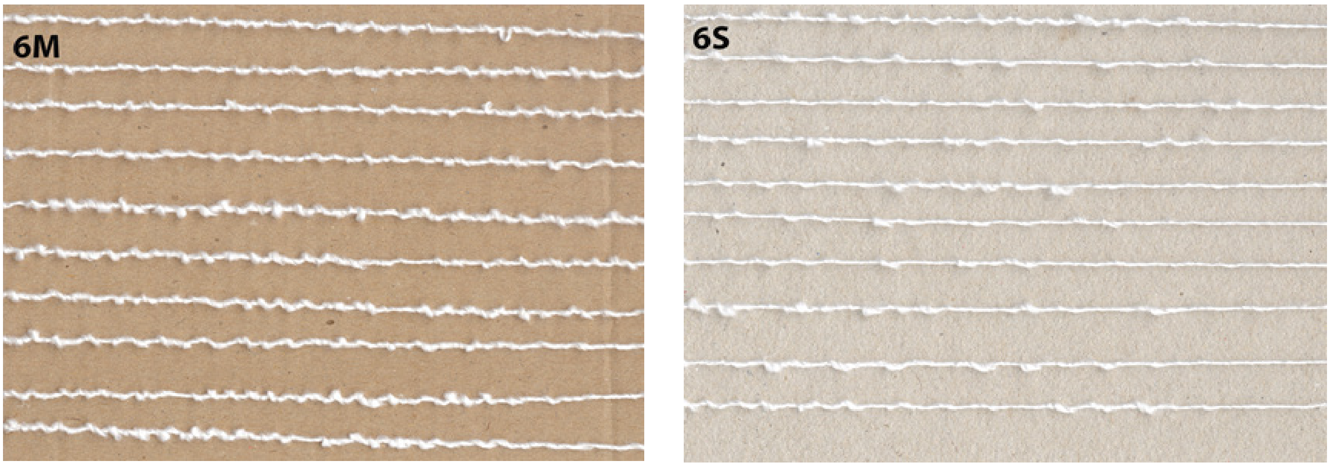


Figure 1. *Examples of cardboards with the glued wet- (left) and dry relaxed yarns (right).*

Table 1. Characteristics of yarn samples.

Yarn type	Material composition	Relaxa-tion	Code
mouliné	97.8% CV 2.2% EL	dry	1S
		wet	1M
	97.8% PAN 2.2% EL	dry	2S
		wet	2M
core-twist	97.8% CV 2.2% EL	dry	3S
		wet	3M
	97.8% PAN 2.2% EL	dry	4S
		wet	4M
core-spun	97.8% CV 2.2% EL	dry	5S
		wet	5M
	97.8% PAN 2.2% EL	dry	6S
		wet	6M
conventional	100% CV	dry	7S
		wet	7M
	100% PAN	dry	8S
		wet	8M

with an elastane core and staple fibre sheath covering). For comparison, ring-spun yarns without elastane from 100% viscose and 100% polyacrylonitrile fibres with the same linear density as for elastomeric yarns were produced (***Table 1***). Mouliné twisted yarns and core-twisted yarns were produced with a nominal twist of 500 S, while single yarns (elastane core-spun yarns and ring-spun yarns without elastane) were produced with a nominal twist of 221 Z and 281 Z, respectively. The yarns were manufactured by the same producer, from the same CV and PAN fibres and under the same production conditions.

Due to the structure, high extensibility and high elastic recovery of the elastane core yarns, significant changes in their thickness were to be expected after wet relaxation, which normally takes place during the care of textile products. Dry relaxed yarns were placed unloaded in a standard environment for 72 hours. The yarns were dynamically wet relaxed with a 2-hour soaking of the threads in water at 30 °C with occasional stirring. Afterwards they were dried in a tumble dryer using the delicate programme.

Preparation of samples/images

The images first obtained for yarn diameter determination with Sadikov's contactless projection-calculation method were also used for the image analysis approach. The individual steps of Sadikov's method were as follows: dry and wet relaxed yarn samples were prepared from the yarn skein as described above. A length of 50 cm was cut from the yarn skein without untwisting the yarn. The upper end of the yarn was attached to A6 size cardboard using a glue gun. There was no contact between the samples and the cardboard. The cardboard with the glued yarn specimens was mounted in a vertical clamp. The lower end of the yarn was preloaded with a minimal loading of 0.3 cN to level the yarn and was then glued to the cardboard. Ten yarn samples were glued onto each cardboard (see ***Figure 1***, page 31). The yarns were not subjected to any pressure, therefore no ovalisation of the yarn cross section was generated. The yarn samples prepared thus were optically scanned (scanner HP ScanJet 4C, USA) at a resolution of 1200 dpi and ten 0.5 × 0.5 cm images were randomly taken from the yarns' scan. These images were then magnified 20-times to a size of 10 × 10 cm and then further treated according to the original Sadikov procedure, i.e. they were printed on paper, and yarn contours were cut and weighed in order to obtain their diameter [27, 28], which were also used for the image analysis approach as explained below.

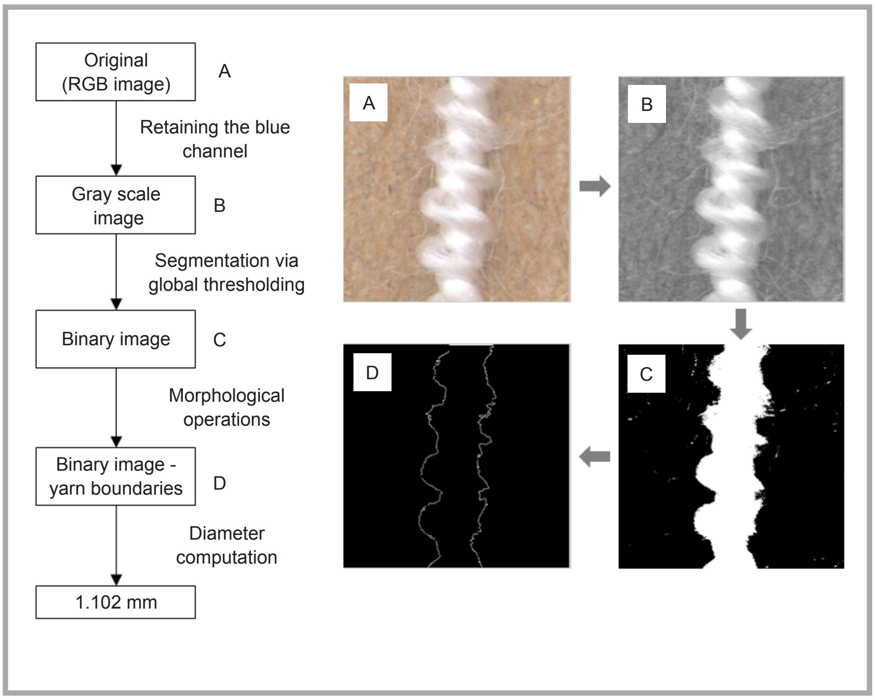


Figure 2. *Image processing workflow for determination of yarn diameter – wet relaxed (M) samples.*

Two sets of yarn samples were investigated: wet relaxed – images designated as M, and dry relaxed – designated as S (***Table 1***). Each set was represented by eight distinctively different types of yarn samples, of which six – numbered 1 to 6 – contained elastane (and were therefore uneven and crimpy) and two – 7 and 8 – were elastane-free, i.e. conventional yarns. The odd-numbered yarns (1M, 3M, 5M, 7M, 1S, 3S, 5S and 7S) were made of viscose and the even-numbered ones of polyacrylonitrile. There were ten samples (images) for each of the 16 yarn types. 0.5 × 0.5 cm digital images (see previous paragraph) were then processed and analysed using a desktop PC and MATLAB® software package as described below. The corresponding codes are provided in the Appendix.

Image analysis

Digital image processing workflows are depicted separately for M and S sets of yarn images in ***Figures 2*** and ***3***, respectively. Since the background on which the M yarn images were acquired differed considerably from that on which S yarn images were obtained, two distinctively different approaches had to be adopted in order to successfully accomplish the segmentation of images and calculation of corresponding diameters within each of the two groups. The key MATLAB functions implemented are given below in *italics*.

With the images of wet relaxed yarns (M) – ***Figure 2*** – the procedure was relatively straightforward. First by retaining only the blue component of the original RGB colour image (A), colour-to-grayscale image conversion took place

(B). After the contrast enhancement step (*imadjust*), the object – yarn – had to be separated from the background, which was conducted by means of intensity thresholding. A suitable threshold value was obtained in the following manner: The image histogram was extracted (*imhist*) and its zero values discarded. After that, the Gaussian function was fitted to the remaining data (*fittype(gauss2'), fit*) and the position of the centre of the peak was considered as the threshold value. This value was used in the subsequent grayscale-to-binary image conversion (*im2bw*) (C). After some morphological filtering applied to eliminate the background artefacts (*bwmorph(b1, 'open'), bwareaopen*) and to remove the interior pixels of the yarn image (*bwmorph(b1, 'remove')*) (D), the distance between the left and right borders of the yarn was calculated for each row in the image. The average distance was considered as the yarn diameter.

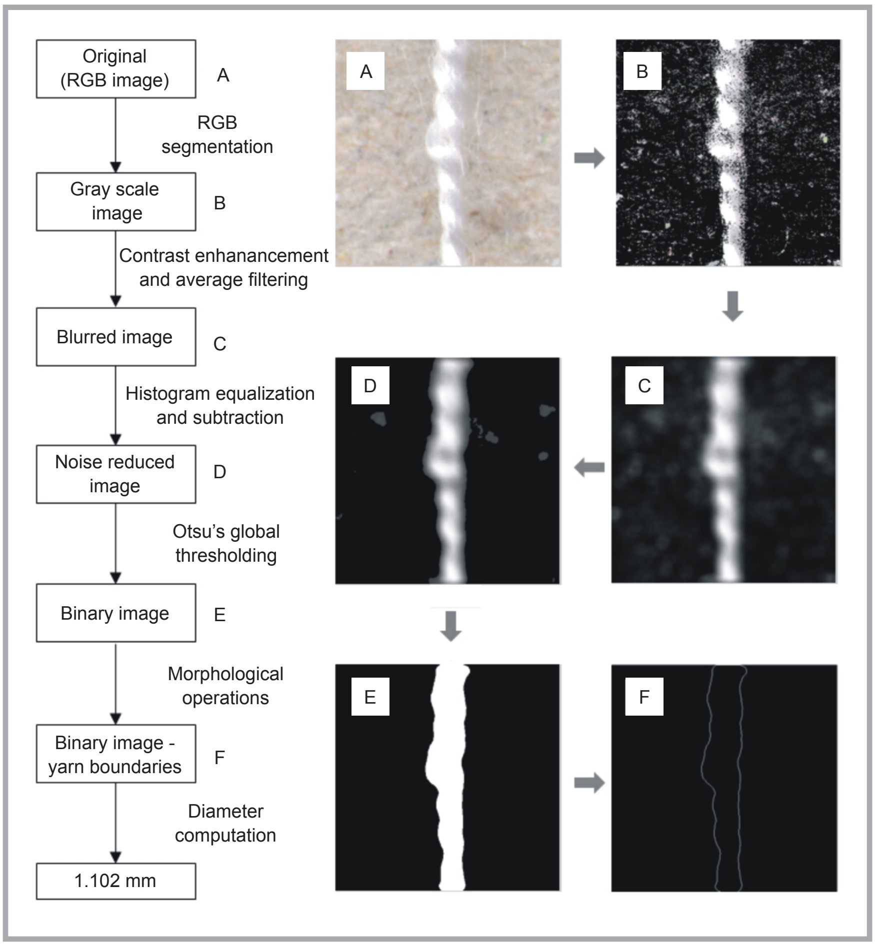


Figure 3. *Image processing workflow for determination of yarn diameter – dry relaxed (S) samples.*

In the case of dry relaxed yarn images (S) – ***Figure 3*** – the simple conversion from the RGB colour image (A) into a grayscale one described above was impossible since the contrast between the yarn and its background was very low in each of the three channels. Instead the grayscale image (B) was converted into its blurred version (C) by applying two spatial filters (*imfilter*) in order to enhance the contrast and to smooth the background intensity. The noise reduced image (D) was obtained by using MATLAB command $R = b–T$, i.e. by subtracting the inverted and histogram-equalized image T ($F = max(max(b))-1-b;$ $T = histeq(F,6)$) from the intensity improved original one ($b = q(:,:,3)$). Otsu's thresholding (*graythresh*) was applied for the grayscale-to-binary (*im2bw*) image conversion. The final processing steps leading to binary images (E) and (F) and yarn diameter computation were similar to those implemented for the M images.

Figure 4 shows contours – edge images in ***Figures 2.D*** and ***3.F*** – superimposed on the original images (A) for one out of 10 samples that were analysed for each of the 16 dry and wet relaxed sample sets.

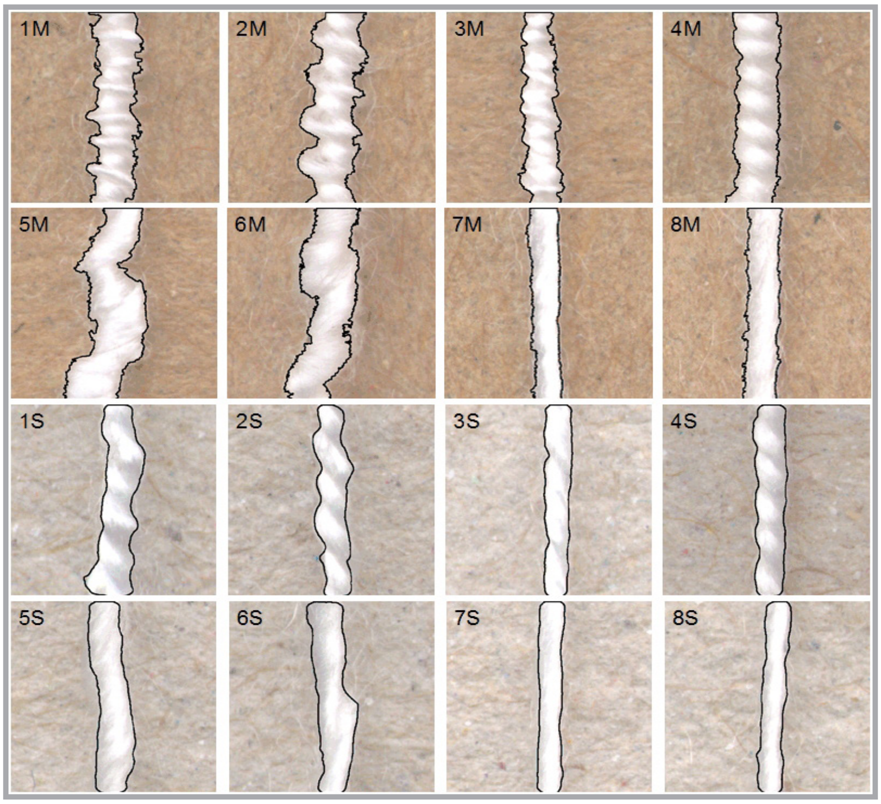


Figure 4. *Original wet relaxed (M) and dry relaxed (S) sample images together with yarn core edges (black borders) as detected by two image processing algorithms.*

Results

Results for the wet relaxed (M; left diagram) and dry relaxed (S; right diagram) yarn diameter computations performed

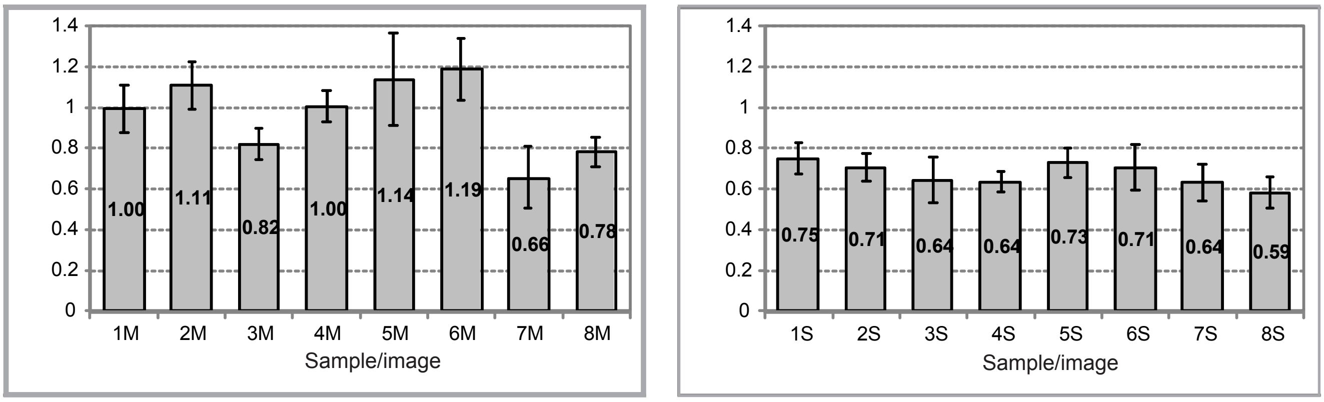


Figure 5. *Yarn diameter mean values and standard deviation error bars for wet relaxed (left) and dry relaxed (right) samples.*

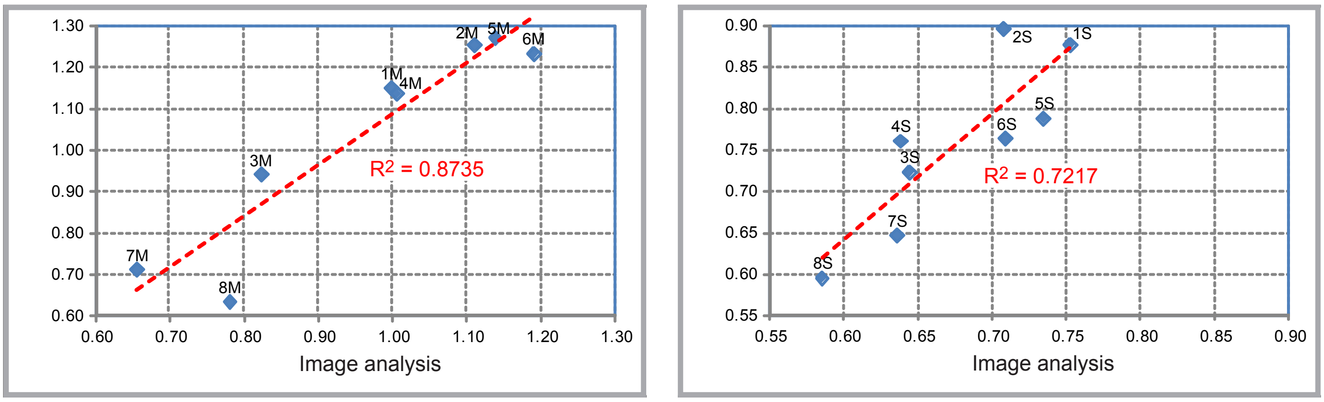


Figure 6. *Comparison between the image analysis-based method and Sadikov's method for yarn diameter determination for wet relaxed (left) and dry relaxed (right) samples.*

by the two image processing procedures described above are shown in ***Figure 5***. The error bars denoting +/– one standard deviation around the mean for each sample/image are displayed as well.

Figure 6 shows the magnitude of the linear correlation between the yarn diameter values obtained with the image analysis-based method and the one proposed by Sadikov for M (left) and S (right) samples.

Discussion

A comparison of M and S yarn diameter mean values (***Figure 5***) leads to several important conclusions: First yarn diameters of the wet relaxed yarns are generally larger than those of the dry relaxed ones, which is due to longitudinal yarn shrinkage taking place during the wet relaxation process. Secondly differences among the mean values of the yarn diameters for both dry and wet relaxed yarns are significantly larger for elasticised yarns (samples 1–6), which exhibit a more pronounced longitudinal shrinkage compared to the non-elasticized ones (samples 7 and 8). Finally yarn diameter variability among the eight wet relaxed samples is much higher than among the dry relaxed ones.

When focusing on the wet relaxed samples only, mouliné (1M, 2M) and core-spun yarns (5M, 6M) are characterised by the largest diameter, while the conventional ones without an elastane core (7M, 8M) exhibit the smallest. Mouliné twisted yarns are composed of elastomeric core-spun yarn and yarn without elastane, both ring-spun. Core-spun yarn has an elastane core and staple fibre sheath covering. During wet relaxation, crimps are formed in these yarns due to non-uniform relaxation shrinkage of the elastane core and fibre assembly in the sheath, which causes a substantial increase in the yarn diameter. Core-twist yarns (3M, 4M) consist of two yarns wrapping an elastane core; they do not include a staple fibre sheath covering of the elastane core, and hence no distinctive crimps are formed that would cause an increase in the yarn diameter.

With the dry relaxed samples, the diameter of the viscose yarns (1S, 3S, 5S, 7S) is larger than that of the corresponding polyacrylonitrile yarns (2S, 4S, 6S, 8S). This trend is exactly opposite to that observed with wet relaxed samples, where, polyacrylonitrile yarns exhibit a more pronounced longitudinal shrinkage compared to viscose yarns during wet relaxation, leading to a yarn diameter increase.

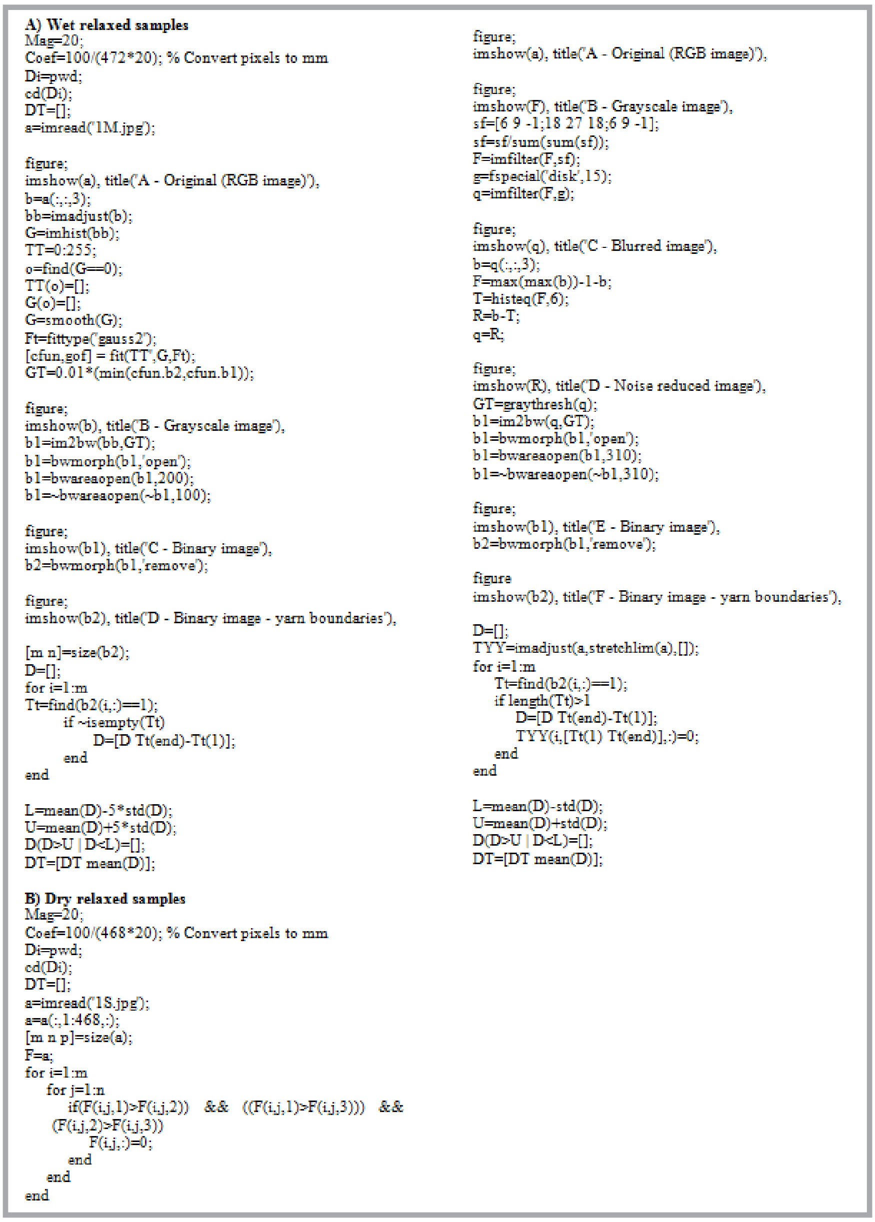
When examining the linear relationship between the two yarn determination methods (***Figure 6***), a higher coefficient of determination (Pearson's correlation coefficient squared, R^2) found in the case of the wet relaxed samples can probably be explained by their more contrasted digital images enabling a more accurate segmentation, i.e. thresholding, than was the case with the dry relaxed images, where the background colour was sometimes very similar to that of the object of interest, i.e. yarn.

It should also be noted that the Sadikov values were almost always higher when compared to the yarn diameter values calculated using the image analysis procedure. This can be explained by the fact that with Sadikov's method, the yarn images were printed and then cut out manually; with this procedure, the protruding fibres were obviously considered as being components of the yarn itself, while the image analysis treated them as a part of the background. As our goal was to measure the yarn core diameter without hairiness, it can be concluded that the image analysis method produces more accurate results.

Conclusions

Accurate yarn diameter determination is crucial for successful prediction of fabric structural parameters such as the width, cover factor, porosity and fabric comfort. Our study demonstrates that with a suitable image processing approach, it is possible to reliably perform the key processing step – image segmentation – and measure the yarn core diameter even in the presence of a low foreground-background contrast, as was the case with our dry relaxed samples. Furthermore the method enables objective determination of the yarn boundaries in contrast to Sadikov's method, in which the yarn boundaries were assessed subjectively. The method presented was validated by comparing its results with those obtained using the conventional contactless projection-calculation method as well as by visual inspection.

In the future, we intend to test various state-of-the-art image segmentation techniques, e.g. Graph Cut and Active Contours, to examine their applicability for yarn diameter assessment.



A) Wet relaxed samples

```
Mag=20;
Coef=100/(472*20); % Convert pixels to mm
Di=pwd;
cd(Di);
DT=[];
a=imread('1M.jpg');

figure;
imshow(a), title('A - Original (RGB image)'),
b=a(:,:,3);
bb=imadjust(b);
G=imhist(bb);
TT=0:255;
o=find(G==0);
TT(o)=[];
G(o)=[];
G=smooth(G);
Ft=fittype('gauss2');
[cfun,gof] = fit(TT',G,Ft);
GT=0.01*(min(cfun.b2,cfun.b1));

figure;
imshow(b), title('B - Grayscale image'),
b1=im2bw(bb,GT);
b1=bwmorph(b1,'open');
b1=bwareaopen(b1,200);
b1=~bwareaopen(~b1,100);

figure;
imshow(b1), title('C - Binary image'),
b2=bwmorph(b1,'remove');

figure;
imshow(b2), title('D - Binary image - yarn boundaries'),

[m n]=size(b2);
D=[];
for i=1:m
Tt=find(b2(i,:)==1);
        if ~isempty(Tt)
                D=[D Tt(end)-Tt(1)];
        end
end

L=mean(D)-5*std(D);
U=mean(D)+5*std(D);
D(D>U | D<L)=[];
DT=[DT mean(D)];
```

B) Dry relaxed samples

```
Mag=20;
Coef=100/(468*20); % Convert pixels to mm
Di=pwd;
cd(Di);
DT=[];
a=imread('1S.jpg');
a=a(:,1:468,:);
[m n p]=size(a);
F=a;
for i=1:m
   for j=1:n
      if(F(i,j,1)>F(i,j,2))   &&   ((F(i,j,1)>F(i,j,3)))   &&
    (F(i,j,2)>F(i,j,3))
          F(i,j,:)=0;
      end
   end
end

figure;
imshow(a), title('A - Original (RGB image)'),

figure;
imshow(F), title('B - Grayscale image'),
sf=[6 9 -1;18 27 18;6 9 -1];
sf=sf/sum(sum(sf));
F=imfilter(F,sf);
g=fspecial('disk',15);
q=imfilter(F,g);

figure;
imshow(q), title('C - Blurred image'),
b=q(:,:,3);
F=max(max(b))-1-b;
T=histeq(F,6);
R=b-T;
q=R;

figure;
imshow(R), title('D - Noise reduced image'),
GT=graythresh(q);
b1=im2bw(q,GT);
b1=bwmorph(b1,'open');
b1=bwareaopen(b1,310);
b1=~bwareaopen(~b1,310);

figure;
imshow(b1), title('E - Binary image'),
b2=bwmorph(b1,'remove');

figure
imshow(b2), title('F - Binary image - yarn boundaries'),

D=[];
TYY=imadjust(a,stretchlim(a),[]);
for i=1:m
   Tt=find(b2(i,:)==1);
   if length(Tt)>1
      D=[D Tt(end)-Tt(1)];
      TYY(i,[Tt(1) Tt(end)],:)=0;
   end
end

L=mean(D)-std(D);
U=mean(D)+std(D);
D(D>U | D<L)=[];
DT=[DT mean(D)];
```

Appendix: MATLAB® codes.

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