A novel method for ring spinning performance evaluation based on Computer Aided analysis of yarn geometry

R. Furferi, L. Governi and Y. Volpe

***Abstract*—**Yarn hairiness and yarn hand represent key parameters to be strictly assessed and controlled in textile processes since they affect many aspects such as visual appearance of yarns (and consequently of fabrics), handle, thermal insulation, pleasant sensation during touch and smoothness. This is particularly true when fancy yarns, such as jaspè or frisè, are produced using ring spinning: colored natural fibers composing the fancy yarns are required to protrude, to some extent, from the yarn core, usually composed by synthetic material, so as to impart the desired properties in terms of smoothness and luster. With the aim of realizing highest performing fancy yarns, a novel ring spinning system, equipped with a double drafting unit, has been realized by Università di Firenze thanks to the contribute of Tuscany Region (Italy). Once the fancy yarns are obtained, the performance of this innovative ring spinning is evaluated by means of a Computer Aided analysis of yarn geometry able to provide a novel measurement of yarn hairiness and to quantitatively define a yarn hand-related parameter.

A Machine Vision system has been devised in order to acquire yarn geometry so that an accurate analysis can be carried out. Such computer aided-based analysis allows to determine two parameters used for determining hairiness and hand: the "equivalent yarn hairiness" and the "yarn hand index".

Such parameters are evaluated for yarns obtained using both the innovative and a conventional ring spinning machine so that the yarns quality can be effectively compared.

Based on the obtained results that the proposed method proved to be suitable and effective for evaluating yarn hairiness within an average error of about 5.40% with respect to the Uster tester.

Furthermore, a good correlation (93%) between objective and subjective assessment of yarn hand was reached.

***Keywords*—** Yarn geometry, Computer Aided analysis, Image processing, yarn hairiness, yarn hand.

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I. Introduction

RING spinning systems are considered crucial processes in producing yarns thanks to their flexibility and to the high quality of produced yarns [1].

Fibers are supplied to the ring-spinning machine in the form of roving; the fiber mass of the roving is, then, reduced by a drafting unit system.

Referring to synthetic-based yarns, such a system (see Fig. 1) is usually composed by a preliminary drafting unit followed by a false twister device, whose function is to increase the volume of continuous yarns, and by a drafting unit.

In the false twister device the yarn is compelled to follow a zig-zag pattern coming into contact with discs of yieldable material, the discs being rotated by friction by (at least) one wear resistant cylinder in contact with them [2].

Afterwards, the fibers lay around one another in concentric helical paths. Yarn from the drafting unit is drawn under the traveler, and then led to the yarn package. In order to wind the twisted yarn on a bobbin tube carried by the spindle, the traveler is required to cooperate with the spindle.

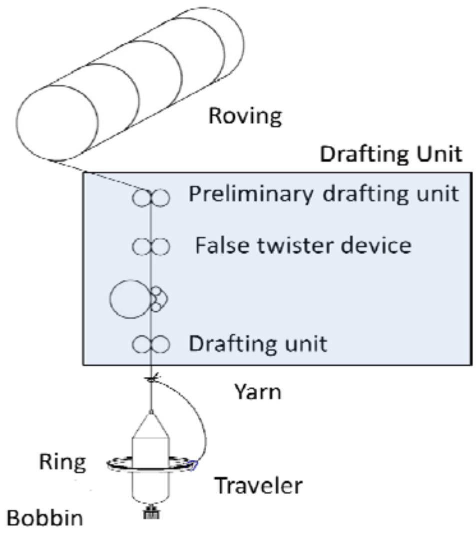

Fig. 1 – Ring spinning machine scheme.

Such a traveler moves on the ring carried along by the yarn it is threaded with. Since the rotation rate of traveler is lower than the spindle, the yarn is winded on a bobbin; a controlled up and down movement of the ring determines the shape of the yarn package.

Among the components of ring frame, drafting unit has the maximum influence on yarn quality and ring performance; in fact, drafting at ring frame considerably influences not only evenness and appearance of fabric, but also rejections due to yarn faults [3]. Accordingly, a modification of the drafting unit architecture may leads to the production of yarns characterized by different properties in terms of quality, aesthetic aspect and “hand”.

This is particularly true when ring spinning is used for creating fancy yarns such as jaspè (a yarn in which two or more fibers of different colors have been twined together to form a mixed or heather-effect color [4]) or frisè. In fact, such yarns are produced using the ring spinning system for creating the yarn core, usually composed by nylon or other synthetic fibers while a subsequent process, i.e. a twisting machine equipped with double roller, is adopted for twinning natural fibers together with the yarn core. Dealing with this issue, in 2009 Tuscany Region (Italy) funded a Research Project whose aim was to develop a new ring spinning system provided with an innovative drafting system able to produce, in a single process, fancy yarns. Such a system (whose scheme is shown in Fig. 2), industrialized in the Laboratories of an important Company operating in Prato (Italy), consists of a double roving unit able to supply both the core fibers (nylon) and the natural fibers that is wounded on such core.

Thanks to this double feeding mechanism, the fancy yarns is created without the need of further processing since one of the roving (i.e. the left one in Fig. 2), continuously fed, provides the synthetic fibers while the other, discontinuously fed, provides the natural, colored, fibers.

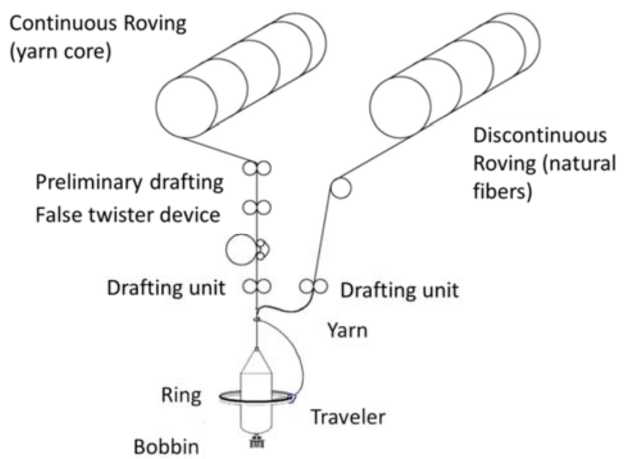

Fig. 2 – Scheme of the new ring spinning system provided with double drafting unit.

In Fig. 3 the devised system is illustrated.

Using this new system, it is possible to obtain yarns by feeding the fibers with an increment equal to 28% with respect to traditional systems and, moreover, it is possible to reduce the percentage of synthetic materials and to decrease costs. On the other hand, the quality of obtained yarns needs to be investigated in order to assess if overall yarn quality is fulfilling the expected results.

In particular, since yarn hairiness and hand effects are among the most important parameters to be evaluated for comparing the performance of conventional and innovative ring spinning systems, a method for measuring these parameters has been devised.

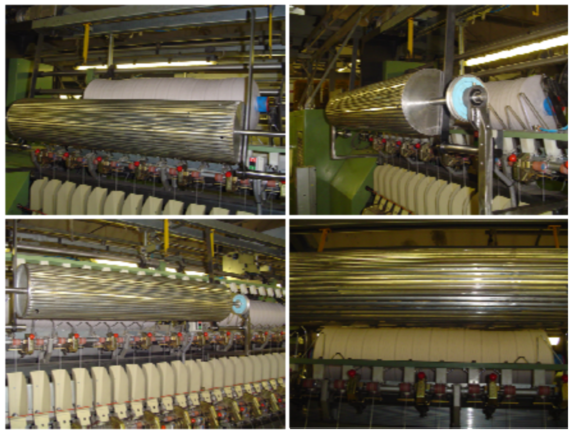

Fig. 3 new ring spinning system provided with double drafting unit.

Hairiness (H) affects both the appearance of yarns (and, consequently, of fabrics) and other apparel parameters such as “hand”, handle and thermal insulation [5]. Hairiness affect, and in its turn is affected, ring production process and is mainly produced by the movement of the traveler. The effect of this process is to allow fibers to to arch out from the yarn core [6-7]. Accordingly, yarn hairiness may be defined as a measure of the amount of fibers protruding from the structure of the yarn [8]. Yarn hairiness assumes an impact which should not be underestimated by textile experts: high hairiness affects the efficiency of weaving and knitting processes due to a tendency to grip and fiber deposits on the machines.

Moreover, it increases the probability of entanglements of adjacent ends possibly causing end breakage. On the other hand, high hairiness (usually with hairs shorter than 3 mm) contributes to soft fabric hand. Accordingly higher hairiness is preferred to lower ones in many knitted fabrics [9].

Despite the huge number of studies on the field, most yarn hairiness determination methods are based on measuring the length and the number of the protruding fiber ends [10].

Among the commonly used equipment, the two most important are the Zweigle G565 hairiness tester and the Uster Tester 3 [11].

The Zweigle G565 tester simultaneously counts the number of hairs at certain distances by a set of photocells. Accordingly it provides the complete distribution of the different lengths of the hairs. In the Uster Tester an infra-red ray goes through a lens and falls on the yarn. The small size of the protruding fiber ends causes their diffraction and refraction which makes the light change its direction. The rays go through the lens assembly which directs them towards a photo-detector. Since the amount of the scattered light depends on the number and the length of fibers, the intensity of photo detector illumination is proportional to the total length of protruding fiber ends. The hairiness is, then, evaluated by means of a "Hairiness Coefficient" H_c defined as the ratio between the total length L_f of protruding fibers (mm) within a given length (mm) L of the yarn [12]:

$$H_c = \frac{L_f}{L} \quad (1)$$

Since the hairiness may considerably change along the linear development of a yarn, in the last years a number of works have been carried out in order to introduce more reliable and realistic indexes.

Guha et al. (2010) [13] presented a new method to measure the hairiness, based on the assumption that the hairs close and parallel to the yarn core would be a better indicator of hairiness, proposing a new parameter, the Hair Area Index.

Recently, Carvalho et al. [14] introduced an image processing based technique for hairiness index evaluation in order to overcome a number of the main drawbacks identified in the traditional yarn testers (e.g. high cost, large volume, high weight, limited resolution and precision in the yarn mass parameters determination).

Some of the authors of the present paper propose, in 2005, an automatic and non-intrusive tool to objectively monitoring the raising process by measuring the height and the density of the fibers emerging from a raised cloth [15]. This work provides the definition of an equivalent height for fibers emerging from raised cloths. In the present work this kind of definition is extended to include yarn hairiness as explained in the following sections.

Yarn Hand (YH) may be qualitatively defined as the tactile sensations resulting from yarn-hand contact. It is related to a mechanism affecting the psychophysical appearances of yarns, leading to a pleasant sensation during touch [16]. Such a mechanism has not been fully explained and understood as yet. Among a number of studies, in particular, the ones performed by Kawabata [17], Luo and Verpoest [18] indicate that it is possible to include hand among subjective feelings evoked by measurable textile characteristics.

II. Objectives and Method Outline

On the basis of the encouraging experiences described by scientific and technical literature and mentioned in the introductory section, the main aim of the present work is twofold:

- to develop a method to perform a Computer Aided analysis of yarn geometry with the aim of (1) measuring yarn hairiness and (2) assessing a preliminary, quantitative, definition of yarn hand.
- to measure, using hairiness and hand obtained by means of the devised analysis method, the performance of the innovative ring spinning system, equipped with two drafting units.

The new method can be outlined as follows.

First, a Machine Vision system is devised in order to acquire yarn geometry so that an accurate analysis can be performed; a set of image processing algorithms are, then, applied to determine two parameters used for measuring hairiness and for "defining" yarn hand: the "equivalent yarn hairiness" and the "yarn hand index". Such parameters are evaluated for yarns obtained using both the innovative and a conventional ring spinning machine. By comparing the resulting measurements the yarn quality is finally assessed.

It is important to highlight that the hairiness definition proposed in this work considerably differs from the definition of coefficient H_c since, as detailed below, it is based on the principle of equivalency between the inspected yarn and an ideal one with all protruding fibers having the same height. A further difference resides in the fact that the proposed method is based on the inspection of a wide portion of the yarn, while other methods are applied to small portions, usually using a microscope. Dealing with yarn hand definition, since in literature only qualitative definitions have been provided, authors propose a qualitative measure with particular reference to fancy yarns.

III. Yarn Hairiness Measurement

With the aim of measuring H a machine-vision system is developed. The main tasks are:

A) Image acquisition.
B) Image rotation.
C) Yarn diameter estimation.
D) Protruding fibers detection
E) Measurement of the yarn hairiness

A. Image Acquisition

Image acquisition is carried out as described in [19]: yarn samples to be inspected are manually placed (by an operator) on a 1200 x 2400 dpi flat scanner and are, formerly, acquired by means of a graphical user interface (GUI), appositely developed in Matlab® environment. A simple algorithm has been developed in order to automatically scanning the area where the yarns are placed (see Fig. 4) and to crop an area equal to 210 x 50 mm. As a consequence, the resulting spatial resolution is equal to $\lambda = 0.175$ mm/pixel; this value may be considered sufficiently accurate for discriminating the yarn hairiness.

Fig. 4 – Example of acquired yarn.

B. *Image Rotation*

Since the yarns are manually placed in the flat scanner, a preliminary rotation of the acquired image needs to be accomplished, as suggested in [14]. In the present work, the yarns are automatically rotated by using the approach provided in [19] evaluating their main axis using a Principal Component Analysis (PCA) based procedure.

Accordingly, let J be a RGB image obtained by scanning a generic yarn; first, a simple transformation to gray scale is performed. The gray scaled image G is, then, thresholded by using the Otzu method [19].

The result consists of a binary image $B(i, j)$ (see Fig. 3) where the yarn is represented by white pixels while the background is represented by black pixels.

Since white pixels in image B represent a cluster of points, it is possible to apply the PCA method to such cluster in order to detect its two principal axis and the rotation α between the major axis and the horizontal direction.

As a consequence, it is possible to rotate the image J by $-\alpha$ so as to obtain a new image J' where the yarn is properly aligned (i.e. the major axis is horizontal).

In Fig. 5 an example of PCA-based rotation of a generic, acquired, yarn is provided.

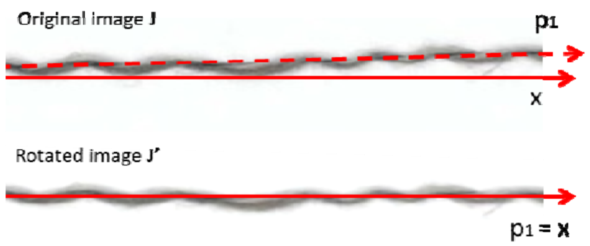

Fig. 5 – Image rotation.

C. *Yarn diameter estimation*

As mentioned above, one of the main aim of the present work is to evaluate the yarn hairiness; as a consequence, the removal from the generic image J' of the yarn core, so as to isolate the protruding fibers, is highly recommended. This is carried out by using an appositely developed procedure, as described below.

Step 1 – Image J' is thresholded using Otzu method thus obtaining a binary image B' (size $n \times m$), interpreted as a 2D unordered point cloud. By definition, point cloud consists of the only pixels of image B' satisfying the condition $b_{m,n} = 1$. Obviously, the number β of points composing the cloud is given by:

$$\beta = \sum_{i,j} b_{i,j} \tag{2}$$

Step 2 – The unordered point cloud can be processed by means of the Multiple Incident Splines (MISs) algorithm proposed by authors in previous works [20, 21]. The final result is to obtain a single polyline for the point cloud; such a polyline is interpolated by means of a B-Spline curve as shown in Fig. 6 (blue curve).

Fig. 6 –Results obtained by applying MISs algorithm.

Step 3 – Let, now, be ℓ the length of the B-spline curve in pixels. using Douglas-Peucker method [22], it is possible to determine the characteristic knots of the B-spline curve: the curve may be split into a number δ of curvilinear segments joining each knot. By computing, for each knot, the normal to the B-Spline curve, the image can be split into a number of regions r_i as shown in Fig. 7 (where, for a sake of clarity, only a portion of the yarn is represented). The portion of B-spline included in such area has length equal to ℓ_i.

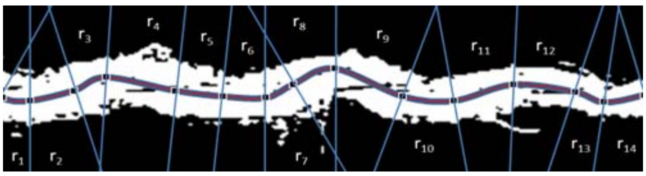

Fig. 7 –Image split into a number of regions r_i .

Step 4 – For each region r_i, the portion of B-spline included in such area is mapped onto a straight line with length ℓ_i by using a second order polynomial mapping function [22]. This 2D to 2D mapping allows to determine the transfer function between the original image of the processed region (r_i) and a "reconstructed" image (i_i) where the yarn principal direction is horizontal. By way of example, in Fig. 8 the region r_9 and the "reconstructed" image i_9 are shown.

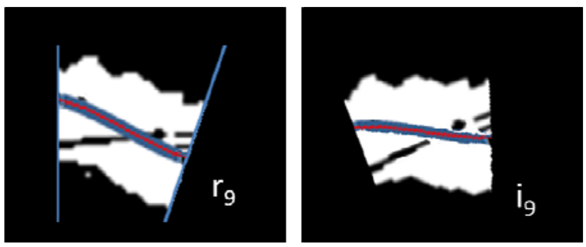

Fig. 8 – Mapping between region and synthetic image i_9 .

Step 5 – Step 4 is repeated for all the regions r_i thus obtaining a set of i "reconstructed" images. Such images are assembled so that, at least, one white pixel of the i^{th} image is shared with a white pixel of the $(i\text{-}1)^{th}$ and of the $(i+1)^{th}$ images, respectively. The result of this step consists of a binary image K representing a "rectified" yarn (see for instance Fig. 9); as a consequence, yarn waviness is discarded by original yarn images.

Fig. 9 – "rectified" yarn

The overlapping of regions r_i assures the "continuity" of the yarn even if a degree of approximation is induced in rectifying it. Such an approximation is needed since the rectification process is based on a discrete points 2D inference that induce numerical approximations (curvilinear points are mapped linearly so that the rectified B-Spline is mapped into a segment that is only approximately straight).

As a consequence, the final length of the rectified B-Spline curve results equal to:

$$\ell' = \sum_i \ell_i - (\delta - 1) \tag{3}$$

Step 6 – Image K is used for determining the yarn diameter according to the following procedure:

FOR each column *j* of image K :

$\Theta(j)$ = the set of all connected components in column j;

$\vartheta(j) \in \Theta(j)$ = the set of all connected components in column j;

$\varphi(j)$ = the number of elements belonging to $\vartheta(j)$; this parameter is defined as "set of local yarn diameters" according to [19].

END

$D_y = \min[\varphi(j)]$

The final result consists of a single value, for each yarn, of the parameter D_y obtained as the min value of all the local diameters for the rectified yarn.

D_y is assumed to represent yarn diameter.

In Fig. 10, the described procedure is depicted with reference to a generic column. In the provided example, two labeled component (clusters k_1 and k_2) are detected by examining a generic column; the local yarn diameter is estimated equal to 10 pixels since the cluster k_2 contains the connected component intersecting the rectified B-Spline (denoted p_1).

In Fig. 11 the red lines represent the boundaries of a yarn identified by using the above described procedure.

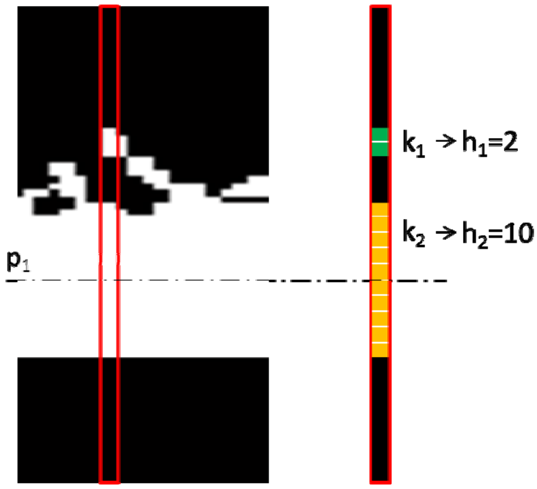

Fig. 10 – Local yarn diameter estimation.

Fig. 11 –Yarn diameter estimation.

D. *Protruding fibers detection*

With the aim of achieving relevant information about the height of fibers protruding from the yarn body, these have to be purged by the yarn core itself. Thus, it is possible to define an image K' (Fig. 12) obtained by setting equal to 0 all the pixels in image K bounded by the estimated yarn diameter (i.e., referring to example provided in Fig. 11, the pixels between the two red lines).

Fig. 12 –Example of an Image K' obtained by setting equal to 0 all the pixels bounded by the estimated yarn diameter.

Once K' is evaluated, a two-dimensional Laplacian of Gaussian (LoG) filter can be used in order to detect the outlines of the emerging fibers in the images. As widely recognized, the output of the LoG operator (image $L_{K'}$) depends on the value of the standard deviation (filter scale) σ. The value for σ is chosen on the basis of the dimension of the smallest particle to be detected by the LoG filter. In the present work a convolution mask with a filter scale $\sigma = 3$ is used in the present work.

In Fig. 13, the effect of LoG filter on the generic image K' is shown. In the background, the LoG filter smoothes the noise due to a not perfectly uniform background, and consequently, it does not find any zero crossing (also called transition) in such a region. Moving toward the fibers, a great number of zero crossings, correspondent to the outlines of the emerging fibers, are detected.

In other words, the LoG filter is able to detect the outlines of the emerging fibers, while the background (and, obviously, the core of the yarn) almost uniformly black.

Fig. 13 –Effect of LoG filter on a generic image K' ; the result consists of a binary image $L_{K'}$.

E. Measuring of the yarn Hairiness: equivalent yarn hairiness

For each of the binary matrices $L_{K'}$ (i.e. for each LoG convoluted image), it is possible to evaluate, row by row, starting from the left upper corner, the number N_r of white pixels, i.e. the crossing of an edge produced by a single fiber thus obtaining the so called "characteristic curve" of a yarn.

In Fig. 14 an example of N_r is shown. Moving downwards from the upper side of the image, the algorithm detects more and more white pixels so that the curve begins to rise.

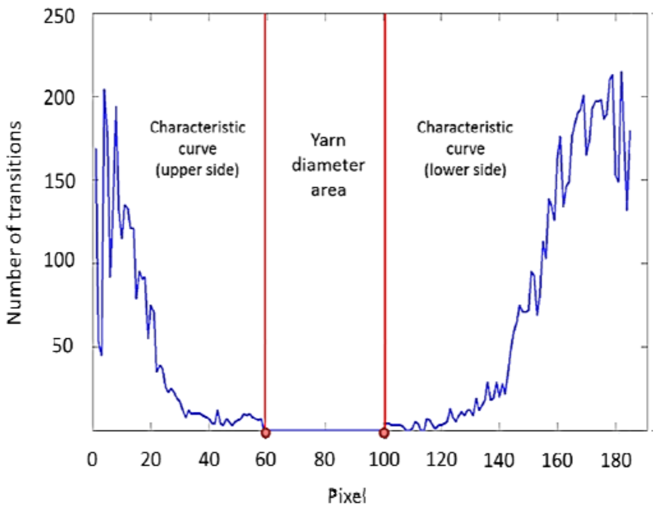

Fig. 14 – An example of characteristic curve.

This is due to the fact that the light diffusive region where the protruding fibers are situated has been reached. This behavior is preserved until a maximum value is attained. After such a value, the curve begins to decrease until the black region (i.e. the yarn core) is reached and the number of transitions, obviously, becomes again zero. Then, the curve begin to rise again since the opposite side of the yarn is reached (since the yarn is approximately cylindrical, if its weaving is neglected, the resulting characteristic curve results bi-modal).

The exemplificative curve shown in Fig. 9 contains all the relevant information about the height of the emerging fibers of the inspected yarn, as will be explained in the next section.

On the basis of the characteristic curve explained above, it is possible to define a new parameter for yarn hairiness: the so called "equivalent yarn hairiness". This may be defined as the protruding fibres height H_e of an ideal equivalent yarn, made of a number $\overline{N}$ of fibres, all having the same height.

Let H_{eu} and H_{el} the distances along the abscissa, in the upper and lower sides of the yarn respectively, between the point c_u (or c_l, see Fig. 10) and the point s_{equ} (or s_{eql}):

$$\begin{aligned} H_{eu} &= \left| s_{equ} - c_u \right| \\ H_{eh} &= \left| s_{eql} - c_l \right| \end{aligned} \tag{4}$$

where the points s_{equ} and s_{eql} are defined by the intersection of the vertical line separating the upper or lower characteristic curve in two equal area portions, and the abscissa axis (Fig.15).

According to its definition, the equivalent yarn hairiness H_e is assumed to be equal to:

$$H_e = \frac{H_{eu} + H_{el}}{2} \quad \text{[pixel]} \tag{5}$$

The above provided equivalent yarn hairiness is expressed in pixels.

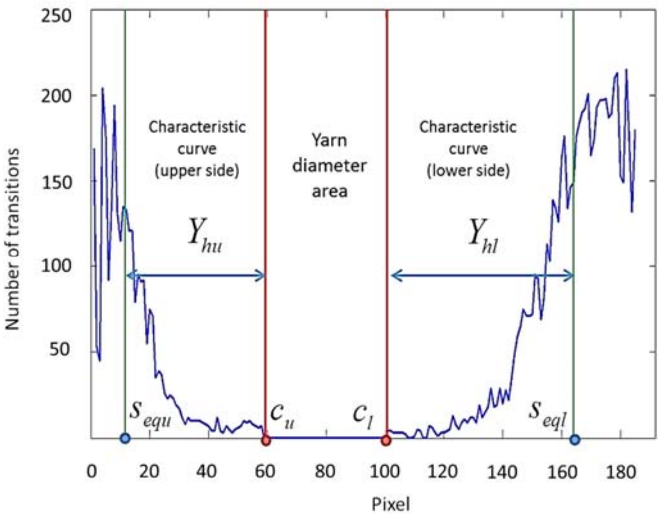

Fig. 15 – Equivalent yarn hairiness.

The same parameter in mm is obtainable by knowing the spatial resolution λ as follows:

$$H_{e[mm]} = \frac{25{,}4 \cdot Y_h}{\lambda} \quad \text{[mm]} \tag{6}$$

The parameter $H_{e[mm]}$ assumed to represent an estimation of the yarn hairiness.

It is important to remark that the spatial resolution adopted for inspecting the yarns is lower than the one used in other works; accordingly the provided measurement has to be considered an approximation of the "real" hairiness of the yarn. On the other hand, the exam of a wider area allows to obtain a more robust measurement with respect to the one obtainable by examining small yarn portions.

IV. Yarn Hand Definition

Since this study refers to fancy yarns composed by a synthetic core and by natural fibers wrapped on it, expert operators suggested that too short fibers are undesired since they reduce the touching feeling (provided by the natural fibers). On the other hand, excessive degree of hairiness is an undesirable property: hairiness imparts "fuzzy" appearance to the yarn [23] and this may reduce its luster. Moreover, too long fibers may cause serious problems in yarn production and in subsequent textile processes.

As a consequence, the best option in "maximizing" hand sensation is to obtain an "average fiber length" able to provide smoothness appearance and more pleasant sensation, thus providing softer feel. *YH* definition depends on a number of factors such as raw materials composing the yarn: yarn diameter (coarser yarns have more hairiness compared to finer yarns), maturity ratio, micronaire value, uniformity index, fiber length, fiber strength and so on [24].

In the present work the definition of H_c is based only on yarn diameter and $H_{e[mm]}$; moreover is referred to fancy yarns.

First, from the equivalent yarn hairiness $H_{e[mm]}$ definition the hairiness coefficient H_c is derived using Equation 1. This operation is not straightforward since the $H_{e[mm]}$ definition refers to (equivalent) fibres average height, while H_c is the total sum of all the fibres heights along a given length. As a consequence, it is necessary to evaluate the number of fibres composing the ideal equivalent yarn $\overline{N}$. In the present work $\overline{N}$ is evaluated by using the approach described in [15] by using a dimensionless normalized pile density index ρ_{norm}, proportional to $\overline{N}$ itself.

Therefore, the hairiness coefficient of sample yarns (H_e) may be evaluated modifying Eq. 1 as follows:

$$H_c = \frac{\rho_{norm} \cdot H_{e[mm]} \cdot \ell}{L} \quad \text{[mm]} \tag{7}$$

Once H_e is determined according to Equation 7, it is possible to provide a quantitative definition of yarn hairiness as follows:

$$I_{YH} = \frac{\rho_{norm} H_{e[mm]}}{c_l - c_u} \tag{8}$$

Where I_{YH} is called "yarn hand index".

Or, in other terms:

$$I_{YH} = \frac{H \cdot L}{(c_l - c_u) \cdot \ell} \tag{9}$$

By the above provided definition, it may be stated that yarns with higher density present higher I_{YH} value when the equivalent height is the same. Reversely, if two yarns are characterized by the same density ρ_{norm} the yarn with higher equivalent height presents higher I_{YH} value.

V. Experimental Results

In order to test the effectiveness of the proposed CAIP method and, at the same time, to assess the performance of the new ring spinning system described in Section 1, 7 different blends have been tested. These are processed using both the innovative drafting unit and the conventional ones. The result consists of a set of 12 yarns with different diameter and hairiness: the first 7 yarns are obtained using the new system (some of them are represented in Fig. 15) while the remaining ones are processed using the conventional one.

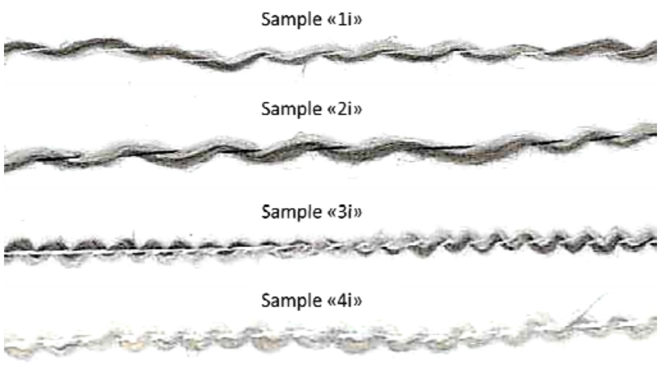

Fig. 15 –Samples of different yarns.

The resulting equivalent yarn hairiness, evaluated by using Equation 6, are compared against the results obtained using the standard Uster Tester with length $L = 20mm$.

Results, delivered in Table I, show that the proposed method proves to be suitable and effective for evaluating yarn hairiness within an average error lower than 5.5% with respect to the Uster Tester.

Regarding the performance of the innovative ring spinning, it can be noticed that H_c values tend to increase for yarns presenting lower hairiness (e.g. Sample 7i vs. sample 7c, Fig. 16) using conventional spinning and, on the contrary, tend to decrease when conventional process lead to too long fibers (e.g. Sample 2i vs. sample 2c).

Referring to the parameter YH, it has been tested on the same set of yarns. On the basis of their experience, a panel of 3 experts [25] classified the yarns into four quality classes in terms of hand effect. Yarns in Quality 4 (Q4) are characterized by the best hand; yarns in Quality 1 are characterized by the worst hand.

Table I: Hairiness experimental results.

	Sample	USTER (H_c)	H	Error (%)
Innovative Process	1i	3.21	3.38	5.30%
	2i	5.43	5.17	4.79%
	3i	4.08	4.33	6.13%
	4i	4.22	4.51	6.87%
	5i	7.52	7.12	5.32%
	6i	5.23	5.68	8.60%
	7i	5.72	6.24	9.09%
Conventional Process	1c	2.98	3.11	4.36%
	2c	6.48	6.32	2.47%
	3c	7.09	7.34	3.53%
	4c	6.4	6.21	2.97%
	5c	8.21	8.87	8.04%
	6c	2.34	2.43	3.85%
	7c	2.76	2.88	4.35%
Mean Error				**5.40%**

Qualities 2 and 3 refer to average hand. In Table II the classification performed by the experts is provided for the 14 tested yarns.

Table II: Quality grading performed by the three experts.

Sample	Expert 1	Expert 2	Expert 3	Experts Average
1i	Q4	Q4	Q4	1.00
2i	Q4	Q3	Q4	0.92
3i	Q3	Q3	Q3	0.75
4i	Q4	Q4	Q3	0.92
5i	Q3	Q3	Q4	0.83
6i	Q4	Q3	Q3	0.83
7i	Q4	Q4	Q4	1.00
1c	Q3	Q3	Q3	0.75
2c	Q3	Q2	Q2	0.58
3c	Q1	Q1	Q1	0.25
4c	Q2	Q2	Q2	0.50
5c	Q2	Q2	Q1	0.42
6c	Q2	Q2	Q2	0.50
7c	Q2	Q2	Q2	0.50

In Fig. 16 a visual comparison between a Q4 sample (sample 1) and a Q1 ones. In order to assess a dimensionless parameter (called "experts average") to be compared with I_{YH}, a score has been assigned to each quality grade as follows: Q1 = 0.25, Q2 = 0.5, Q3 = 0.75 and Q4=1. The final score of each yarn, i.e. the experts average EA, is then computed as follows:

$$EA = \frac{Q1 + Q2 + Q3 + Q4}{4} \tag{10}$$

In Table III the experts average and the objective evaluation of is I_{YH} are compared using the ratio ξ defined as follows:

$$\xi = \left(\frac{I_{YH}}{\max(I_{YH}) \cdot EA} \right) \tag{11}$$

When ξ is close to 1, the subjective evaluation is very similar to the one obtained using the proposed method. The more the ratio ξ differs from 1 and the lower correlation is found between the subjective and the objective measurement.

Results in Table III show that, averagely, $\xi = 0.93$ i.e. the accuracy in measuring I_{YH} with the proposed method is about 93% with respect to the measurement provided by the experts.

Table III: Comparison between EA and I_{YH}.

Sample	EA	I_{YH}	ξ
1i	1.00	0.673	0.96
2i	0.92	0.621	0.97
3i	0.75	0.499	0.95
4i	0.92	0.688	1.07
5i	0.83	0.518	0.89
6i	0.83	0.499	0.86
7i	1.00	0.699	1.00
1c	0.75	0.506	0.97
2c	0.58	0.387	0.95
3c	0.25	0.142	0.81
4c	0.50	0.321	0.92
5c	0.42	0.264	0.90
6c	0.50	0.307	0.88
7c	0.50	0.299	0.86
		Mean Value	**0.93**

VI. Comparison between Conventional and Innovative Ring Spinning Systems

As stated in section II, one of the main objectives of the present work is to compare the quality of yarns obtained using two different technologies: a standard ring spinning system and the innovative double draft-based one. As depicted in Table IV, the innovative process tends to increase the yarn hairiness with respect to the conventional one when it is around 3 – 3.5 and to decrease it when it is greater than 6.

Referring to yarn hand, as showed in Table V the new process allows to highly increase yarn hand thus proving to be effective in obtaining frisè and jaspè yarns with very good hand as demonstrated also in the example provided in Fig. 16

when samples "1i" (on the left) and "1c" (on the right) are compared.

Table IV: Comparison in terms of hairiness between conventional and innovative ring spinning.

Sample	H **conventional**	**Sample**	H **innovative**	**Delta**
1c	3.11	1i	3.38	8.7%
2c	6.32	2i	5.17	-18.2%
3c	7.34	3i	4.33	-41.0%
4c	6.21	4i	4.51	-27.4%
5c	8.87	5i	7.12	-19.7%
6c	2.43	6i	5.68	133.7%
7c	2.88	7i	6.24	116.7%

Table V: Comparison in terms of yarn hand between conventional and innovative ring spinning.

Sample	I_{YH} **conventional**	**Sample**	I_{YH} **innovative**	**Delta**
1c	0.506	1i	0.673	33.0%
2c	0.387	2i	0.621	60.5%
3c	0.142	3i	0.499	251.4%
4c	0.321	4i	0.688	114.3%
5c	0.264	5i	0.518	96.2%
6c	0.307	6i	0.499	62.5%
7c	0.299	7i	0.699	133.8%

Fig. 16 – Visual comparison between sample ii and 1c.

VII. Conclusion

The present work proposes a novel method for ring spinning performance evaluation based on Computer Aided analysis of yarn geometry. The method automatically and objectively evaluates the yarn hairiness by detecting a characteristic curve describing the behavior of yarn protruding fibers and by defining an equivalent yarn hairiness parameter. Moreover a parameter for objectively defining yarn hand is proposed.

The method has been tested on an innovative ring spinning system whose development was performed within a Project financed by Tuscany Region (Italy).

Based on the obtained results that the proposed method proved to be suitable and effective for evaluating yarn hairiness within an average error of about 5.40% with respect to the Uster tester. In particular it was possible to measure with a non-intrusive technique an equivalent yarn hairiness to be correlated to the hairiness coefficient (H_c). Furthermore, a good correlation (93%) between objective and subjective assessment of yarn hand was reached.

The mathematically determined parameters were finally used to test the effectiveness of a new ring spinning system provided with a double drafting unit. Results demonstrated that the new spinning system is capable of increasing yarn hand and to homogenize the hairiness, thus allowing to obtain smoother jaspè and frisè yarns.

Future work, by means of an extensive experimental campaign, will be addressed to the generalization of the proposed approach in order to deal with different kinds of yarns (e.g. ribbon, boucle, mohair etc.).

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