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Estimation of the Inter-Yarn Channel Inlet Diameter in Textile Materials Using Structured Light 3D Micro-Scanning

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Abstract
In this paper, a novel method of estimation of the diameter of inter-yarn channel inlets in textile materials, in particular fabrics, is described. This method is based on 3D micro-scanning with structured light. After 3D reconstruction of the fabric surface, one uses the so called "cutting" plane perpendicular to the fabric to get the cross-sections and measure the diameters of the channel inlets. The mean value of the diameters measured estimates the size of the channel inlets. A standard 3D scanner for dental applications was applied for the research. As an important result, we present the correlation of the diameters and other parameters of the fabrics chosen with the air permeability.

Key words: *3D scanning, structured light, inter-yarn channels, fabrics, textile materials, air permeability.*

Introduction

Nowadays 3D scanning and object reconstruction is becoming very popular. It has many applications both in medicine and industry and can be widely used in daily life, e.g. in computer games [9]. In the textile domain, one can use 3D scanning to measure the human body and fit the appropriate clothes [11]. 3D scanning and modelling can be used in the fashion industry to design new clothes. There are different methods of 3D reconstruction, e.g. some of them use the *Direct Linear Transformation* (DLT) [1], and the others are based on the concept of disparity [3]. There are passive and active methods that use illumination to reconstruct the object. Among them, the ones with structured and modulated light are of the greatest interest today [6,7,8]. In medicine, 3D scanning is widely used in dental applications for the reconstruction and design of prostheses [10].

In this research we propose the use of a typical dental 3D scanner for the identification of inter-yarn channel inlets. The original method described in this paper uses the statistical approach to estimate the diameters of the channel inlets. This work is based on the experience achieved in previous research [1, 2]. The final aim of the study is to evaluate the impact of the channel geometry on air and vapour permeability, as well as heat transfer through textile materials, in particular fabrics.

3D micro-scanning of textile materials using structured light

The concept of using structured light 3D scanning to estimate the size of inter-yarn channel inlets was implemented using a standard 3D dental scanner, ***Figure 1***, equipped with 2 high resolution monochromatic CCD cameras and a projector which generates different patterns of structured light. The object is mounted on a movable table which rotates the object around 2 axes while illuminating with the structured light – ***Figure 2***. The patterns can vary with time while the object is rotated and images are acquired. The system can operate at 40 µm spatial resolution with comparable accuracy. The scanning volume is 90 × 80 × 55 mm, which is enough for small samples of textile materials. The scanner is controlled by dedicated software which generates files with a cloud of pixels in 3D in the standard format **.stl*. Such files can be easily read by the application prepared for analysis in MATLAB®.

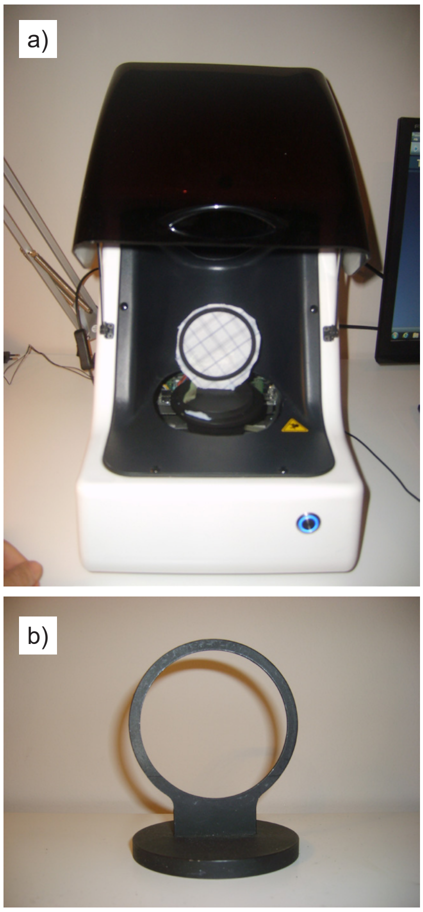

Figure 1. *3D scanning system used for dental purposes, Scanner 88SCAN [10] (a), and the handle of textile material (b).*

For this research a special circular handle was designed to place and fix a fabric in the scanner – ***Figure 1***. The important issue of the method proposed is that the sample under test is flat but not stretched. The handle is mounted on the built-in rotation table – ***Figure 2***. Typically the entire scanning process takes a minute, and then within the next minute the reconstruction is performed. Then the **.stl* file is exported to the application **Tex3D** prepared in MATLAB®.

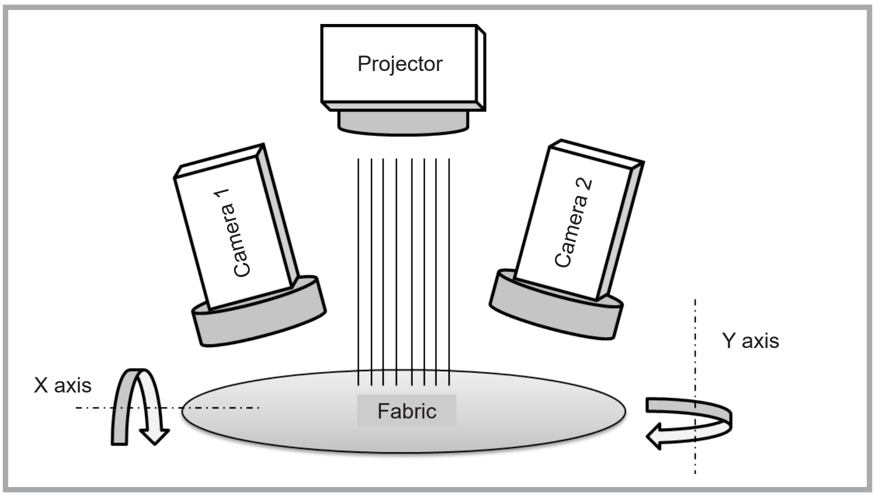

Figure 2. *Concept of measurement of the geometrical parameters of inter-yarn channel inlets using 3D scanning with structured light.*

New method for estimation of the diameter of inter-yarn channel inlets

The method of evaluating the inlets of inter-yarn channels proposed uses the cloud of points reconstructed by the 3D scanner. One assumes that the fabric is a plane with a certain roughness, but this is not always true due to slight bending and deformation, which is the main reason that at this stage of the research, the operator needs to manually select the appropriate part of the textile material.

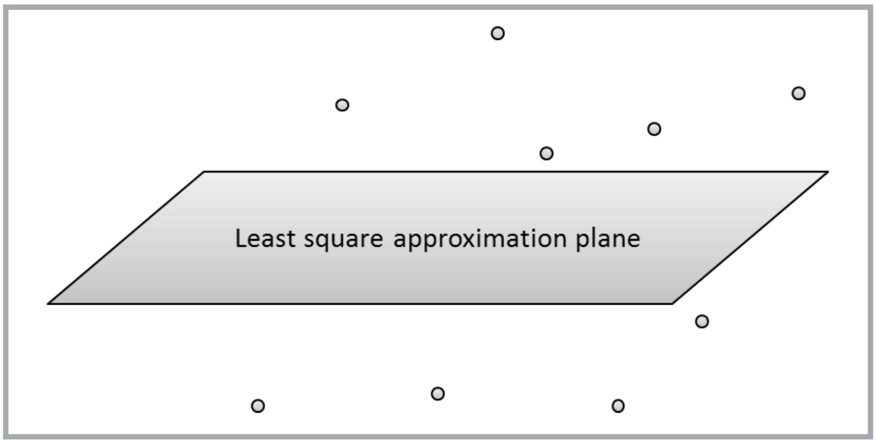

Figure 3. *Cloud of points reconstructed by 3D scanner and least square approximation (fabric plane).*

The method of measuring the diameters of the inlets of inter-yarn channels consists of the following stages:

1. determining the fabric plane that separates the points in the 3D space using the least square criterion – ***Figure 3***,
2. finding the cutting plane perpendicular to the fabric and to the vector arbitrarily chosen – ***Figure 4***,
3. calculating the cross-sections of the fabric using the cutting plane – ***Figure 5*** (see page 90),
4. smoothing the cross-section by low-order polynomial approximation – fitting curve, ***Figure 5***,
5. measuring the distances between cross-points of the cross-section and the fitting curve – ***Figure 5***,
6. calculating a histogram of the distances and the 1st order statistical parameters.

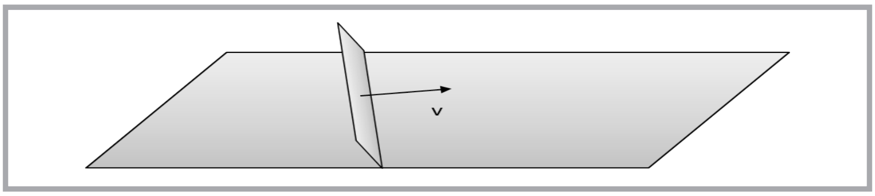

Figure 4. *Cutting plane perpendicular the fabric plane and arbitrarily chosen vector v.*

The key issue of the method proposed is to determine the cross-section of the fabric, which is done by defining the "cutting" plane perpendicular to the fabric that is shifted along a chosen direction, defined by vector *v* perpendicular to the "cutting" plane (***Figure 4***). Vector *v* is chosen manually in order to get the most preferable cross-sections of fabrics of periodically varying or oscillating shape, ensuring proper reconstruction of the inlet of inter-yarn channels.

Once the cross-sections is found, one performs smoothing by low-order polynomial approximation, as shown in ***Fig-***

Table 1. *Exemplary statistical parameter of channels' inlets.*

Parameter	Exemplary results Fabric 91/2009
Standard deviation, mm	0.125
Mean value, mm	0.213
Kurtosis	10.841
Skewness	1.891
Variance, mm^2	0.016
Min-max value (standard deviation/mean), %	58.73
Median, mm	0.196
Max, mm	1.600
Min, mm	0.0001

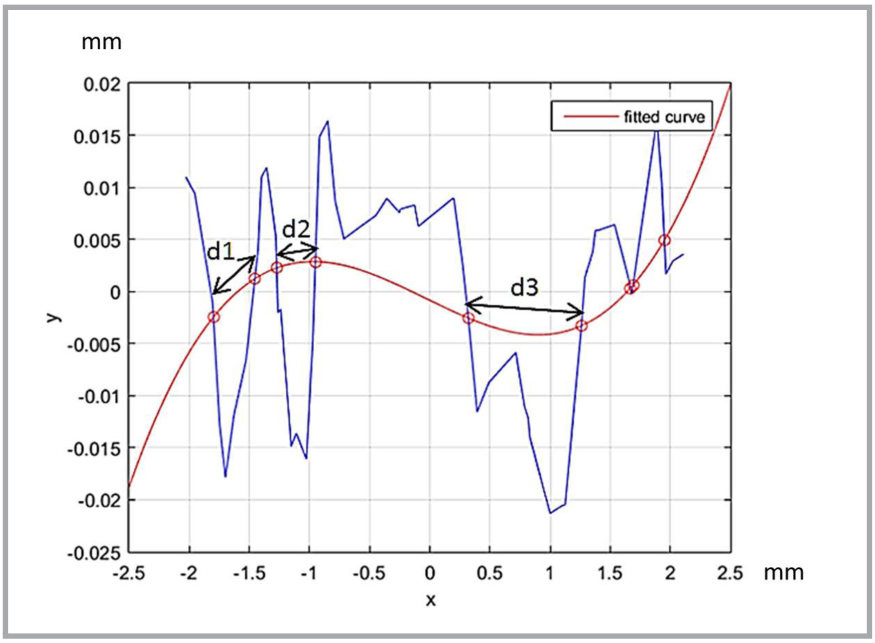

Figure 5. *Low-order polynomial approximation, cross-points and distances between them.*

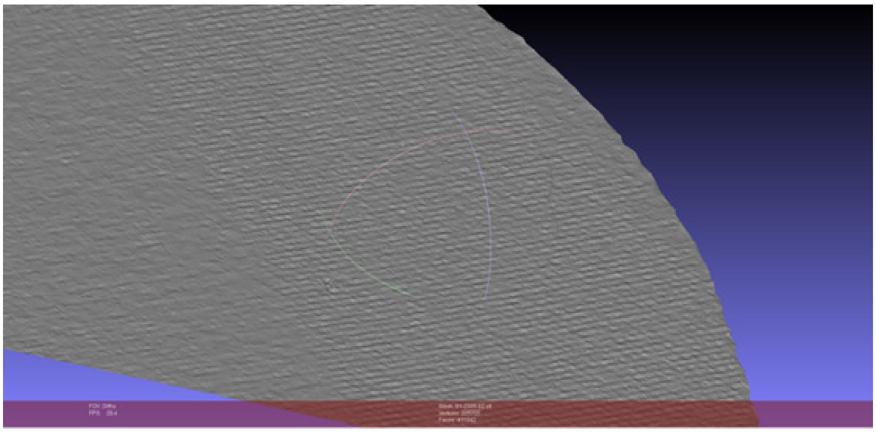

Figure 6. *Rendered surface of the exemplary fabric.*

ure 5. We proposed the 3rd or 4th order approximations. Then the cross-points are calculated and one measures the distances between them.

Next the cutting plane moves in the direction of vector *v* and the new distances are measured. Finally one calculates histograms of the distances and statistical parameters. An exemplary set of statistical parameters are presented in ***Table 1***. The mean and median values are of main interest. According to our experience, the median value seems to be the most correlated with the air permeability of the fabrics.

The method proposed implements several algorithms for data and signal processing. At the very beginning, the surface of the fabric is calculated using the linear regression in 3D space and the least square approximation. The "cutting" plane is determined simply by using the basic analytical geometry equations. Meanwhile triangulation has to be performed to get the cross-section of 2 surfaces in the 3D Cartesian coordinate system. The well-known methods in photogrammetry are used, which are in-built in the MATLAB® program. The MATLAB® program simplifies significantly the entire implementation of the method proposed. The important stage of the whole method is the reduction of the dimensionality of the cross-section. Typically it is in 3D space, and can be reduced to 2 dimensions using Principal Component Analysis (PCA) [4, 5].

Program Tex3D for inter-yarn channel inlet measurements

In order to estimate the diameters of the frontal part of the inter-yarn channels, a program entitled **Tex3D was** developed in the MATLAB® environment. This program reads **.stl* files from the 3D scanner, containing 3D coordinates of clouds of points. In order to better visualise the reconstructed surface, triangulation is performed as shown in ***Figure 6***. The cloud of points can be rendered both in MATLAB® and in the software

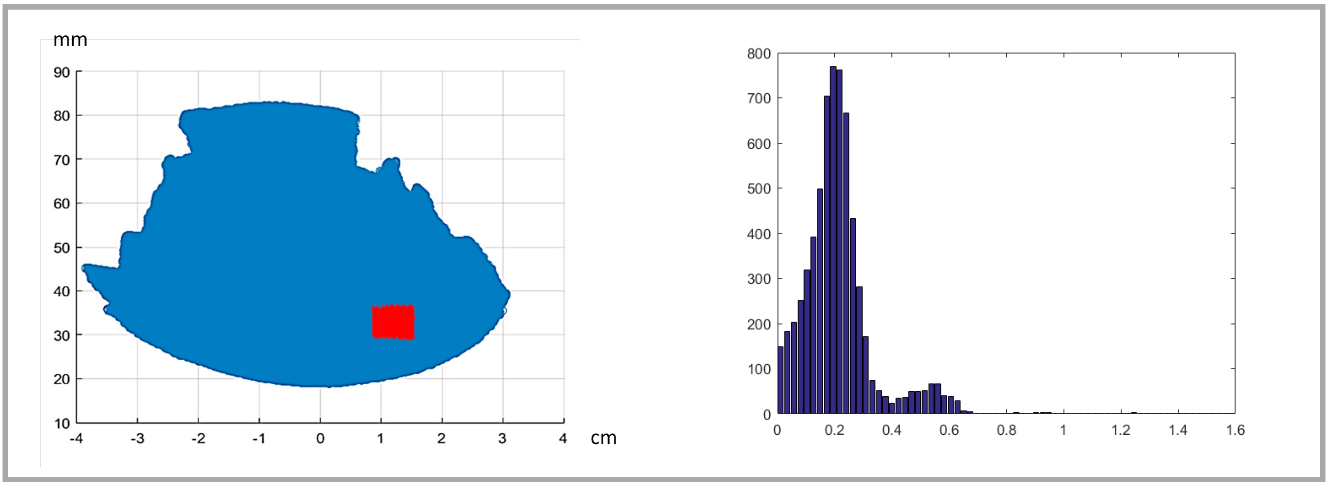

Figure 7. *Selected part of the fabric used for further analysis.*

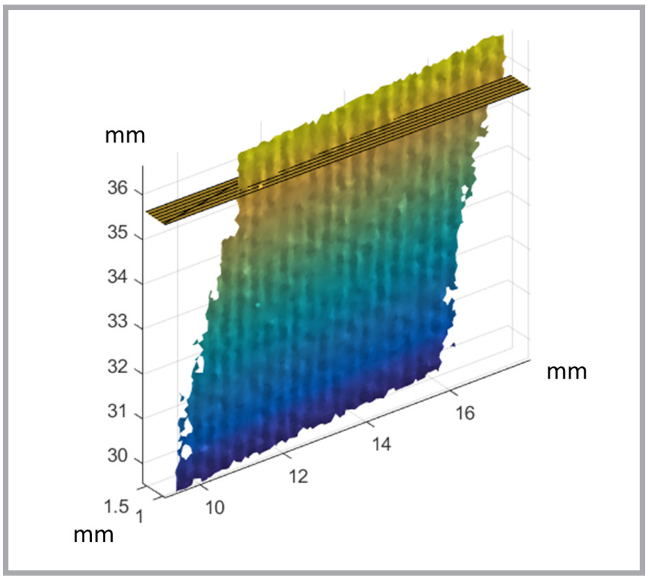

Figure 8. *Cutting plane which allows to obtain the cross-sections of fabric.*

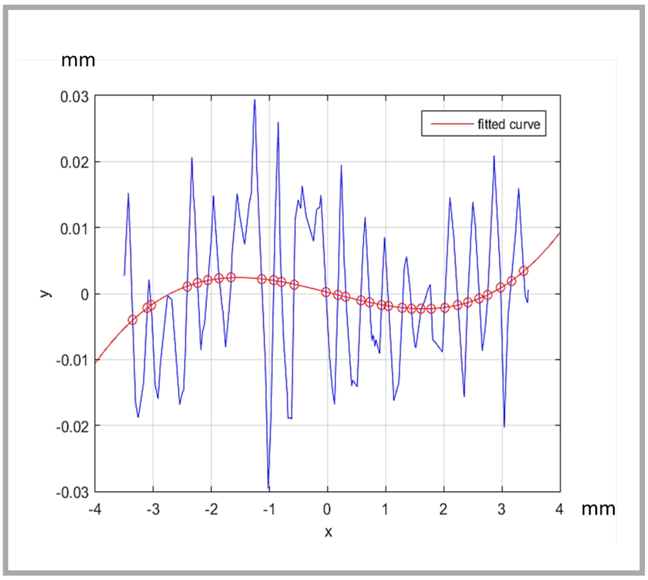

Figure 9. *Exemplary cross-section of fabric and its low-order polynomial approximation.*

of the scanner. The result of the rendering is a rough surface that can be rotated and illuminated with varying light to see details of the object analysed (***Figure 6***).

During the experiments, the entire cloud contained about 600 000 points, about 10 to 15% of which were selected for further 3D analysis, i.e.: 6000 - 9000.

Typically the reconstructed surface is not planar. The distortion is very small but enough to see it while rotating. The first action undertaken by the operator is to select the most planar part of the surface analysed. The results are presented in ***Figure*** *7*, where one can notice from this stage of the algorithm that the selected part of the fabric is fully dimensioned and can be measured.

The next step of the method is to define "the cutting" plane perpendicular both to the one analysed and to an arbitrarily chosen vector, as has been already mentioned above. As a result, "the cutting" plane is used for calculating the cross-section of the fabric – ***Figures 8, 9***. Both surfaces are represented in 3D space. The cutting plane moves in the direction indicated by the arbitrarily chosen vector *v*, allowing to collect hundreds of cross-sections and calculate the statistical parameters describing the inlets of channels of the fabrics.

The crucial element of the method proposed is estimation of the diameters of the channel inlets, performed by approximation of the cross-sections and finding the cross-points of the original curve and the fitting one, as shown in ***Figure 9***. The **Tex3D** program allows to select the area of interest and then set the range of moving the cutting plane – ***Figure 10***. The user can choose the order of polynomial used for the approximation. At each stage of the algorithm, one can visualise the results in graphical form. Finally the statistical parameters of the channels' inlets are calculated – ***Figure 10***.

One of the important result of the method presented is the histogram of distances. The diameters of the channels' inlets are estimated by the distances between cross-points obtained by smoothing the cross-section of the fabric – ***Figure*** *5*. ***Figure 11*** presents an exemplary histogram.

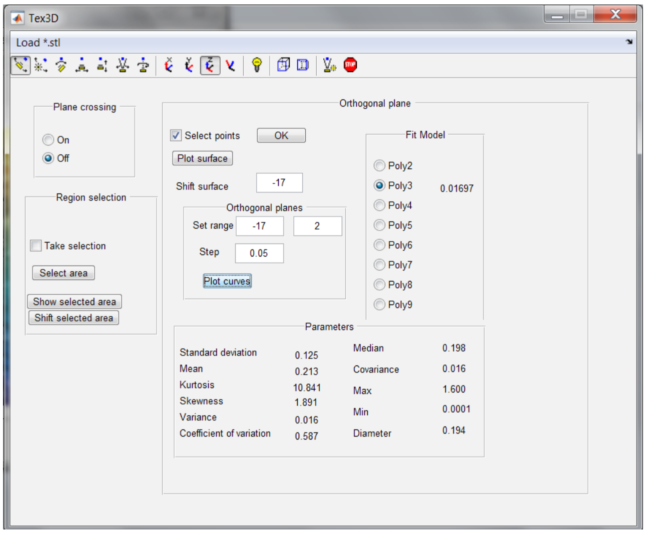

Figure 10. *Main window of Tex3D program.*

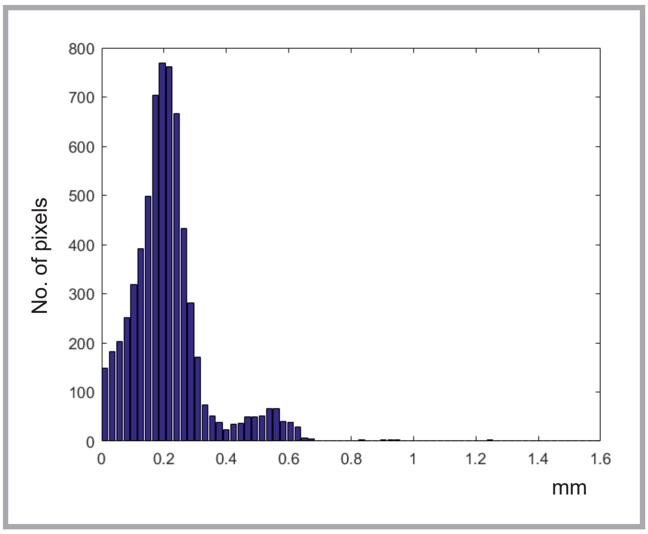

Figure 11. *Exemplary histogram of distances between cross-points.*

Table 2. Statistical parameters for inter-yarn channel inlets for 7 fabrics obtained using the method presented.

Parameter	Fabric						
	91/2009	Andromeda 150	Gustaw 6/150	KM 1/150	Kornel 150K	LJ 1/05	LJ 4/06
Mean value, mm	0.206	0.327	0.250	0.489	0.311	0.340	0.279
Standard deviation, mm	0.121	0.245	0.184	0.260	0.240	0.177	0.141
Kurtosis	9.803	5.641	8.714	3.090	8.863	13.038	6.720
Skewness	1.956	1.448	2.063	0.261	2.030	2.298	1.119
Variance	0.015	0.060	0.034	0.068	0.057	0.031	0.020
Min-max, %	58.73	74.89	73.71	53.22	76.99	52.14	50.45
Median, mm	0.196	0.284	0.211	0.503	0.278	0.327	0.278
Max, mm	0.938	1.499	1.300	1.552	1.844	1.683	1.066
Min, mm	0.001	0	0	0	0	0	0

Table 3. Correlation between selected parameters of fabrics.

	Air permeability	Inlet diameter	Surface mass	Thickness	Sett of weft	Sett of warp
Air permeability	1.0000	0.4018	-0.5929	-0.4358	-0.7017	-0.6005
Inlet diameter		1.0000	0.1555	0.3202	-0.2015	-0.3713
Surface mass			1.0000	0.9642	0.8935	0.7447
Thickness				1.0000	0.8502	0.6390
Sett of weft					1.0000	0.8745
Sett of warp						1.0000

The diameter of channel inlets is estimated by the mean or median value of the set of distances between the cross-points. Typically these values are very close to each other.

Results

Results are presented in a table with statistical parameters of the sets of distances that estimate the diameter of the frontal part of the channels – ***Table 2***. One assumes that the diameter is estimated either by the mean or the median value of the set of distances (diameters). These values are very similar. One should notice the relatively high value of standard deviation of the diameters measured. It has to be underlined that the distances measured are in the range of 0 - 500 µm. The 3D scanner used in this research measures the distances with an uncertainty of about a few tens of µm. Therefore the uncertainty of measurement expected using the method proposed cannot be very high. However, it is still at an acceptable level. On the other hand, in this research we confirm the usefulness of structured light scanning in the estimation of the geometrical parameters of fabrics in 3D space. For more precise measurements, one needs better equipment.

In ***Table 2*** there are 7 different fabrics used in this research, each of which has different technological parameters, such as the sett of weft and warp, thickness, surface mass and various weaving strands. In addition, each fabric is made of different raw material with different porosity as well as channel inlet size, its length and volume. More data on the fabrics used in the research have been already presented [2]. All the parameters of the fabrics considered were measured in standard ambient conditions, i.e.: T_{air} = 20 ± 1 °C and RH = 65 ± 3%.

One can notice that the kurtosis and skewness are positive. Both these parameters characterise the shape of the histogram of the channel inlet diameters. The relatively high value of kurtosis denotes that the distribution of the diameters is not flat. It has a dominant value, well defined and close to the mean and median ones. The positive value of the skewness means that the histogram is not symmetrical (in this case left-modal). In practice, it denotes that there are values much higher than the mean and median ones, as is shown in ***Figure 11***. An important conclusion can be drawn if one compares the values of kurtosis and skewness with the variance and min-max range. The histograms of the diameters are rather spread, but with a significant number of measurement results gathered around the mean and median values.

As has been already mentioned above, this research is a part of a larger program leading to finding the correlation between the inter-yarn channel structure and exploitative parameters of textile materials, such as air permeability and vapour, as well as the heat transfer rate. At this stage of the research, we were able to find the correlation between the diameters measured and air permeability through the fabrics only. This correlation is not very high (r = 0.4), but it is the expected result – ***Table 3***. The low value of the correlation is due to the fact that the air permeability of fabrics depends not only on the diameter of the channel, but also on the thickness and other textile parameters .

An interesting conclusion can be drawn by analysing the results in ***Table 3***. The highest correlation of air permeability was obtained for the sett of wrap and weft (|r| = 0.6 - 0.7). It is an expected result, as well as the fact that these correlations are negative. The relatively low correlation of the air permeability of the fabric with its thickness and surface mass is typical for low values of these parameters, denoting that the thickness and surface mass of the fabric are not as important for air permeability as the sett of wrap and weft. A very high correlation was found between the surface mass and thickness of the material (r = 0.96).

All the results presented here confirm the general conclusion that the air permeability through fabrics depends not only on the diameter of the inter-yarn channels but also on many other parameters thereof.

Conclusions

1. The main conclusion of the research presented in this paper is that structured light scanning is a new, effective, cheap and fast method for characterisation of the surface of textile materials in microscale. It can be used to estimate the inter-yarn channel size, especially in its frontal part. The mean and median values are good estimates of the diameter of channel inlets.
2. The correlations between air permeability and technological parameters of fabrics are relatively low (|r| < 0.7). The correlation of air permeability and the diameter estimated has a low value - r ≈ 0.4, being a positive value, which confirms the correctness of the measurement approach proposed. The low value of this correlation confirms the general conclusion that the air permeability of fabrics depends on differ-

ent parameters, not only on the channels' inlet diameter. The highest correlation was found between the surface mass and thickness of the fabric (r = 0.96). Similarly the thickness and the sett of wrap and weft are highly correlated as well (r = 0.85 - 0.96).

3. An additional interesting conclusion can be drawn from the results in *Table 3*. The diameter of the inter-yarn channels estimated using the method proposed is correlated the most with the air permeability of the fabrics in comparison to the other technological parameters. Finally one can generally conclude that air permeability (probably the transfer of vapour and heat as well) depends on various geometrical, structural and physical parameters of fabrics, and in order to model, predict and design the air, vapour and heat transfer through fabrics, multivariate data analysis is required.

References

1. Więcek P, Polipowski M and Więcek B. *Stereovision System for 3D Analysis of the Geometrical Properties of Fabrics. Fibres and Textiles in Eastern Europe* 2015; 23, 1(109): 61-67.
2. Polipowski M, Więcek P, Więcek B and Jasińska I. Study of Woven Fabric Structure Using 3D Computer Image Analysis for In-Depth Identification of Thread Channels. *Fibres and Textiles in Eastern Europe* 2015; 23, 2(110): 33-39.
3. Nalpantidis L, Christou S G and Gasteratos A. Review of Stereo Vision Algorithms: From Software To Hardware. *International Journal of Optomechatronics* 2008; 2: 435–462.
4. Jolliffe I T. *Principal Component Analysis*. 2nd ed., Springer, 2002.
5. http://www.mathworks.com/help/stats/examples/fitting-an-orthogonal-regression-using-principal-components-analysis.html.
6. Jang W, Je C, Seo Y and Lee S W. *Structured-Light Stereo: Comparative Analysis and Integration of Structured-Light and Active Stereo for Measuring Dynamic Shape. Optics and Lasers in Engineering* 2013; 51, 11: 1255-1264.
7. Hansard M, Lee S, Choi O and Horaud R. *Time-of-Flight Cameras: Principles, Methods and Applications*, Springer Brief in Computer Science, 2012.
8. https://en.wikipedia.org/wiki/Structured-light_3D_scanner#/media/File:3-proj-2cam.svg
9. http://www.kscan3d.com/
10. http://www.88dent.com/
11. http://www.tc2.com/

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