A COMPREHENSIVE PHYSICAL MODEL FOR LIGHT REFLECTION IN TEXTILES FOR COMPUTER GRAPHICS APPLICATIONS

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Abstract:

This paper is concerned with the optical properties and 3D modelling of textile structures (yarn, woven and knitted product). A method for establishing a set of statistical surface parameters for a fibre from atomic force microscopy measurement is proposed. This technique is adapted for yarn. Nevertheless, AFM measurements are impossible for this structure, so a virtual profiler has been developed. Finally, several reflectance models are compared. The Lafortune model is the most adapted to predict reflectance properties of yarn. The correlation of estimated and measured surface parameters is processed to make the model physically plausible for textile materials. Once this task has been achieved, this modified model is implanted in a ray tracing program for more realistic computer graphic application in the field of textiles.

Keywords: textile structure, 3-D modelling, reflectance models, CAD of textiles

I. Introduction

Today, in order to assess the appearance of any given textile, individual samples must be physically produced and subordinated to yarn availability. Moreover, specific machines must be employed. This awkwardness could be largely alleviated by the development of computer models. Although research for a more realistic representation of textiles is important, only limited work has been done in the field of optical properties. In fact, a large part of this work deals with the draping behaviour of various structures (woven or knitted product)[1]. But, only a few attempts have been made to improve the quality of textile rendering with optical bases. The quality of a rendered image depends to a great extent on the accuracy of the reflectance model used. In the past decade, computer graphics have seen the application of several physically based models, including surface parameters. Nevertheless, physical bases are merely optical, and surface parameters are not connected to real measurements. Thus, this study proposes theoretical and experimental results to improve knowledge of the optical properties of a textile structure in relation to real surface characteristics. Two steps are involved. The first is to give an estimation (by optimisation techniques) of the surface parameters from optical measurements and reflectance models. The second is to link the estimated surface parameters and the measured ones. Finally, ray tracing is used to produce a rendered image with a modelled textile structure. This structure can be obtained either with 3D modelling or with 3D measurement.

This study is the first to propose a valid reflectance model which is totally physically based, because both the optical and surface characteristics of the textile are included in the model. The first step is concerned with the yarn structure; future works will consider woven and knitted products.

II. Evaluating the surface and morphological parameters

The main key feature is to establish a link between the material's surface and morphological characteristics and those obtained from the optical models, which are described in the next section. Two kinds of measurements are carried out. Two structures are concerned: fibre and yarn.

II.1 Systematic measurements

This kind of measurement is applied to yarn alone, because the parameters evaluated are yarn count and twist. All theses measurements are performed on a Yarntester (Superba, France).

II.2 Geometric and surface measurements

Two sample scales must be analysed. First, the only active optical elements are fibres. To access surface parameters, in this case, a particular scanning probe microscopy is involved: atomic force microscopy. Then, fibres are processed to form a yarn, but evaluating the yarn surface parameters is not an easy task. In fact, no device is currently available to carry out this work, and so we have developed a specific process to scan the yarn surface.

II.2.1 Fibre surface parameters

The Atomic Force Microscope (AFM) probes the surface with a sharp tip, a couple of microns long and often less than 100Å in diameter. The tip is located at the free end of a cantilever that is 100 to 200µm long. Forces between the tip and the sample surface cause the cantilever to bend or deflect. A detector measures the cantilever deflection as the tip is scanned over the sample. These deflections allow a computer to generate the map of surface topology. Several forces typically contribute to the deflection of an AFM cantilever. The force most commonly associated with AFM is an interatomic force called the Van der Waals force. Figure 1 shows the map of surface topology of an acrylic fibre.

However, this image is not valid for establishing fibre surface parameters. The general shape must be subtracted (otherwise all measurements are inverted to isolate the fibre roughness. The measurements described present a measure of the fine, closely spaced, random irregularities of the surface texture. The roughness of the fibre illustrated by Figure 1 is represented by Figure 2.

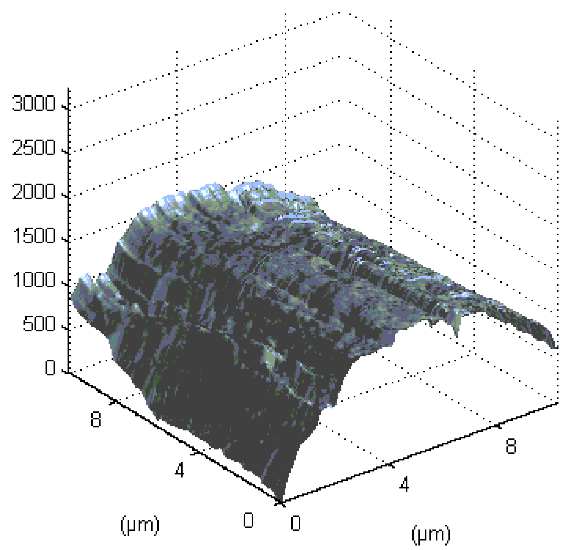

Figure 1. AFM image of surface topology of an acrylic fibre

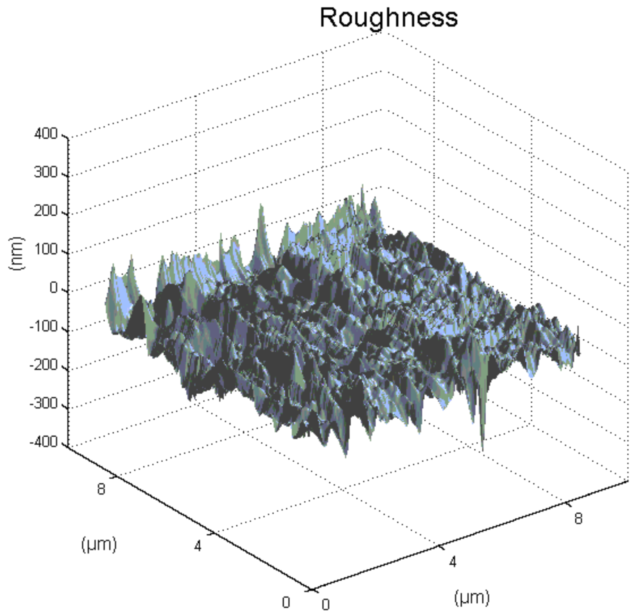

Figure 2. Roughness of the fibre illustrated by Figure 1

From the roughness data, several statistical parameters are established which form two groups; the first is obtained from height data and the second from slope data.

The parameters that are establish from height data are:

- the ***roughness average (h_{fibre})***, the arithmetic mean of the absolute values of the surface departures from the mean plane;
- the ***root mean square roughness ($rmsH_{fibre}$)***, obtained by squaring each height, then taking the square root of the mean;
- the ***height skewness (Skh_{fibre})***, the asymmetry of the surface about the mean plane. This parameter is like a mean-cubed roughness;
- the ***height Kurtosis (Kh_{fibre})***, the peakedness of the surface. It provides information about the 'spikiness'of a surface, or of the sharpness of the amplitude density function, which does not necessarily mean the sharpness of individual peaks and valleys;
- the ***roughness standard deviation (σ_{fibre}).***

Slope data are processed to provide the following parameters:

- the ***root mean square slope ($rmsS_{fibre}$)***, obtained by squaring each slope, then taking the square root of the mean.
- the ***slope skewness (Sks_{fibre})***.
- the ***slope kurtosis(Ks_{fibre})***.

II.2.2 Yarn transversal section analysis

Many parameters could be established from the yarn transversal section analysis. Nevertheless, care should be taken to isolate this section. First, the yarn structure is fixed with an epoxy resin. Once the set resin-yarn has hardened, a small section is taken with a precision saw. Each section is observed by an optical microscope. The final step is to determine the yarn contour. We have developed a program to achieve this task by mean of image processing. Figure 3 shows such a section once the program has completed its run.

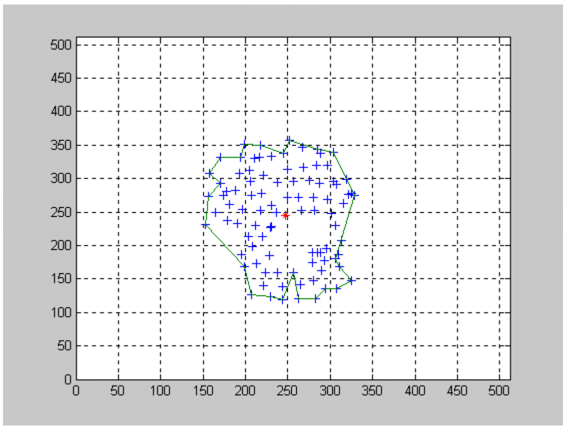

Figure 3. Yarn contour (straight line) and fibre centre positions (+) from an acrylic yarn

Thus, the following parameters established from the yarn contour and the original image of the section are as follows:

- the ***yarn porosity (P_{yarn})***, one minus the number of pixels "'fibre'" divided by the number of pixels 'yarn'.
- the ***yarn surface (S_{yarn})***, the number of pixels 'yarn'.
- The ***fibre density (D_{fib})***, the number of fibre centres ('+' from Figure 3).

II.2.3 Virtual surface profiler

The image of the yarn transversal section obtained from the previous subsection is exploited. The image is screened, and scanned by a cursor in such away that the first position in the first column corresponding to a fibre pixel is stored. The profile of the section is obtained when all columns are screened. Figure 4 shows the profile obtained from the yarn transversal section image.

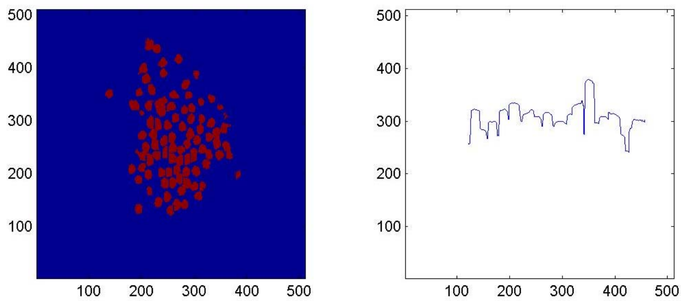

Figure 4. Yarn profile obtained from the yarn transversal section image

Then, the first image is extruded and a rotating motion is applied, and so a virtual yarn transversal section is obtained, and a new profile can be established. This process is repeated in order to produce a virtual yarn with a sufficient length to represent a rotating motion of 360°. When all profiles are juxtaposed, Figure 5 is obtained.

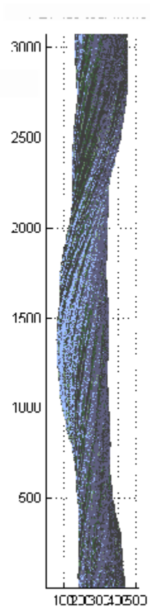

Figure 5. Image of surface topology of an acrylic yarn processed with the virtual surface profiler

These data are analysed by means of the program developed for fibre surface analysis. Thus, the same parameters are established (see subsection ***II.2.1)***.

III. Estimating the surface parameters from optical measurements and models

III.1 Modelling surface reflection

Reflection is the process by which incident flux leaves a stationary surface from the incident side without changes in frequency. A surface may not reflect the same quantity of flux for each possible incident direction. It is also possible that the surface may cause scattering of the incident light into a distribution of reflection directions. Nicodemus et al.[??] presented a defining paper which provided a standard framework for the description of light reflection from a surface. The fundamental contribution of this work was the presentation of the bi-directional reflectance-distribution function (BRDF). This provides a flexible and general mathematical function with which to describes the anisotropic reflection of incident flux from most surfaces. The BRDF, f_r, describes the distribution of reflected light as a function of the incoming and outgoing directions and relates radiance to differential irradiance. The BRDF of a surface can be measured for a set of surface orientation and illumination geometries using a gonioreflectometer. In our case, the incident direction is 45°, and the observation directions are 0°, 15°, 30°, 45° and 60°. Use of the resulting data is, however, impractical as it may contain noise and will not cover the entire domain of the BRDF. It is therefore desirable to be able to represent the BRDF in terms of a functional model. Such a model would need to encapsulate all the features of the surface but should not be expensive in terms of computing time. Ideally, the model would have parameters with a physical meaning to describe the surface's reflection characteristic.

Several models have been established. Nevertheless, care should be taken when attempting to construct a BRDF model. When considering a physical model of light reflection, it is imperative that the resulting total BRDF function has a proper normalisation. A reflectance model that does not yield a correct energy balance is useless when considering the physical process of light reflection. Failure to ensure this could cause the model to predict more light energy to be reflected than is incident on a surface. Thus, the following models have been considered:

- Phong model[2], $f_r=f(\rho_d,\rho_{dd},n_s)$.
- Ward model[3], $f_r=f(\rho_d,\sigma_x,\sigma_y)$.
- Schlick model[4], $f_r=f(r,p)$.
- Lafortune model[5], $f_r=f(\rho_d,n_d,n_s)$.
- Oren/Nayar model[6], $fr=f(\rho_d,s)$.

with:

- ρ_d, diffuse reflectance.
- ρ_{dd}, directional diffuse reflectance.
- n_d, diffuse exponent.
- n_s, specular exponent.
- r, roughness factor.
- p, isotropy factor.
- σ_i, rms slope in the direction i.

These models are presented as a function of the unknown parameters. An optimisation is processed to identify these parameters.

III.2 Results

Three sets of samples are considered. The first contains cotton yarn produced by conventional spinning (CAF cotton), the second includes cotton yarns produced with open-end spinning (OE cotton). Acrylic yarns manufactured by conventional spinning constitute the third set (CAF Acrylic). Five different yarn counts are produced for each sample set. Measurements are carried out with the geometries specified in the previous subsection for two configurations: (1) the yarn parallel to the incident beam and (2) the yarn perpendicular to the incident beam. Figure 6 shows the different reflectance spectra for the three sample sets and the two configurations.

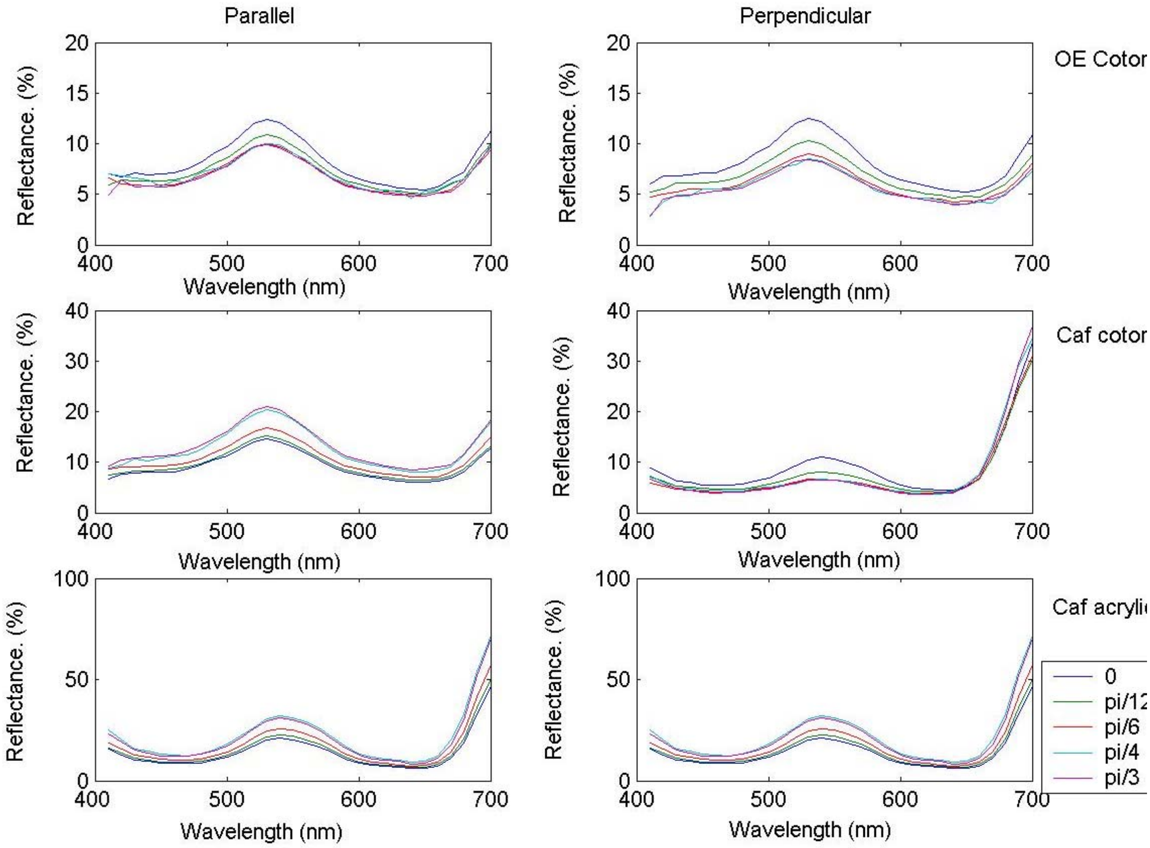

Figure 6. Examples of reflectance spectra for the three sample sets and the two instrumental configurations

Table 1 indicates the error between predicted and measured reflectance value.

Table 1. Prediction error observed with the different models for the three sample sets and the two configurations; ⊥ - perpendicular, - ‖ - parallel

Model	Parameters	CAF Cotton		OE Cotton		CAF Acrylic	
		⊥	‖	⊥	‖	⊥	‖
Lafortune	ρ_d, n_d, n_s	0.0054	0.0031	0.0002	0.0001	0.0005	0.0031
Schlick	r,p	0.0043	0.0442	0.0016	0.0024	0.0029	0.0043
Ward	$\rho_d, \sigma_x, \sigma_y$	0.0015	0.0031	0.0045	0.0007	0.0055	0.0054
Oren/Nayar	ρ_d,s	0.0016	0.0034	0.0001	0.0007	0.0013	0.0016
Phong	ρ_d, ρ_{dd}, n_s	0.0054	0.0048	0.0030	0.0001	0.0282	0.0160

This table shows that model performance is not uniform. Nevertheless, several exhibit satisfactory results, particularly the Lafortune model, which combines this behaviour with a low computational time. Thus, only this model is considered for the next step: the correlation of the estimated and measured surface parameters.

IV. Estimated and measured surface parameters correlation

Matrices of correlation show that:

- ρ_d is correlated to the yarn count (0.9310), D_{fibre} (0.9214) and S_{yarn} (0.7230).
- n_d is correlated to the yarn count (0.9532), Skh_{yarn} (0.6329).
- n_s is correlated to the yarn count (0.9365), Ks_{yarn} (0.7435).

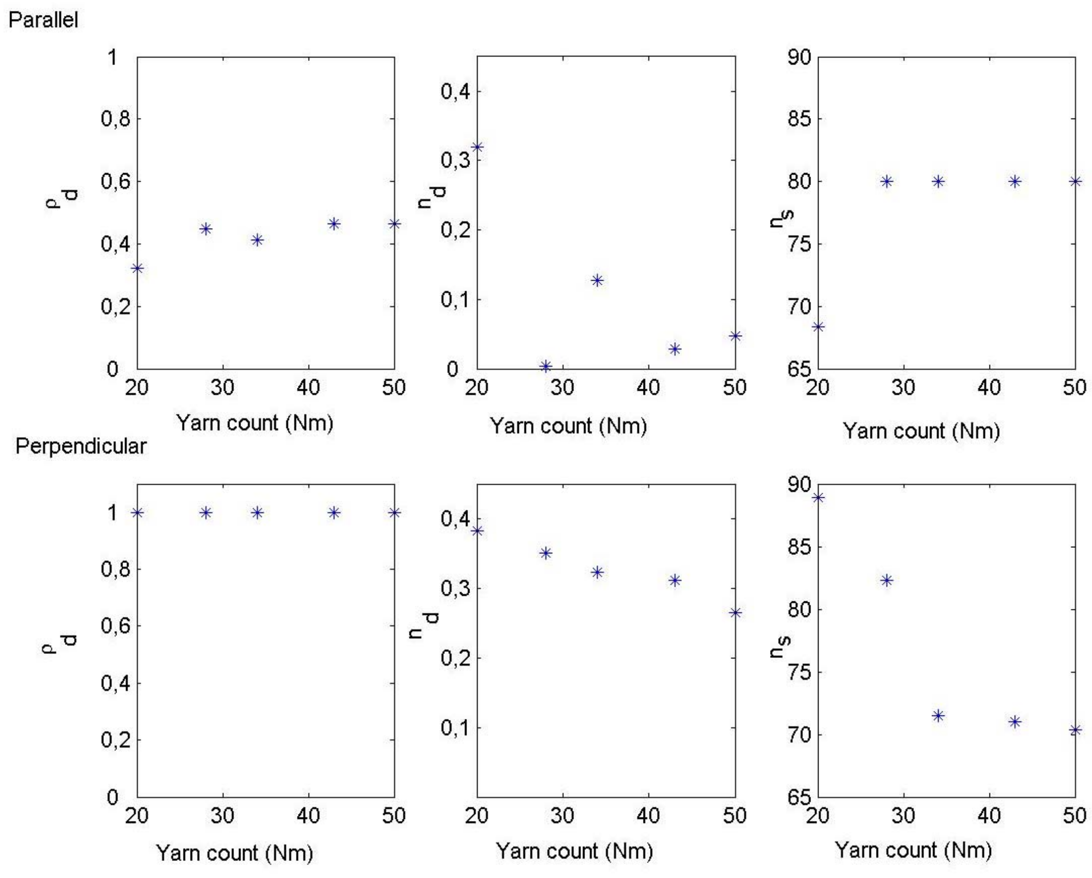

Figure 7. Evolution of Lafortune model's parameters as a function of the yarn count for the sample set CAF cotton

V. Computer graphics application

V.1. Modelling cloth

Several methods can be considered to obtain a virtual garment. Many works publications have considered mechanical considerations. On the other hand, a garment can be entirely modelled by a computer graphic modeller. We use a hybrid method based both on mechanical consideration and graphic applications. Figure 8 shows a shirt structure obtained with this technique.

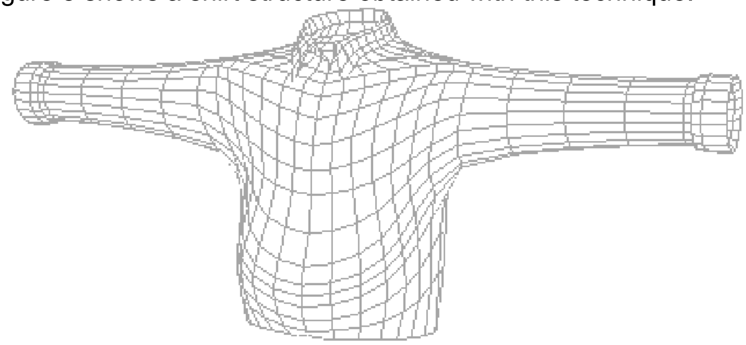

Figure 8. Virtual shirt structure

V.2 Virtual fashion parade

Finally, the Lafortune model is applied to virtual clothing which is characterised by the parameters identified in the previous section. Figure 9 shows the result for the previous shirt and for a walking man.

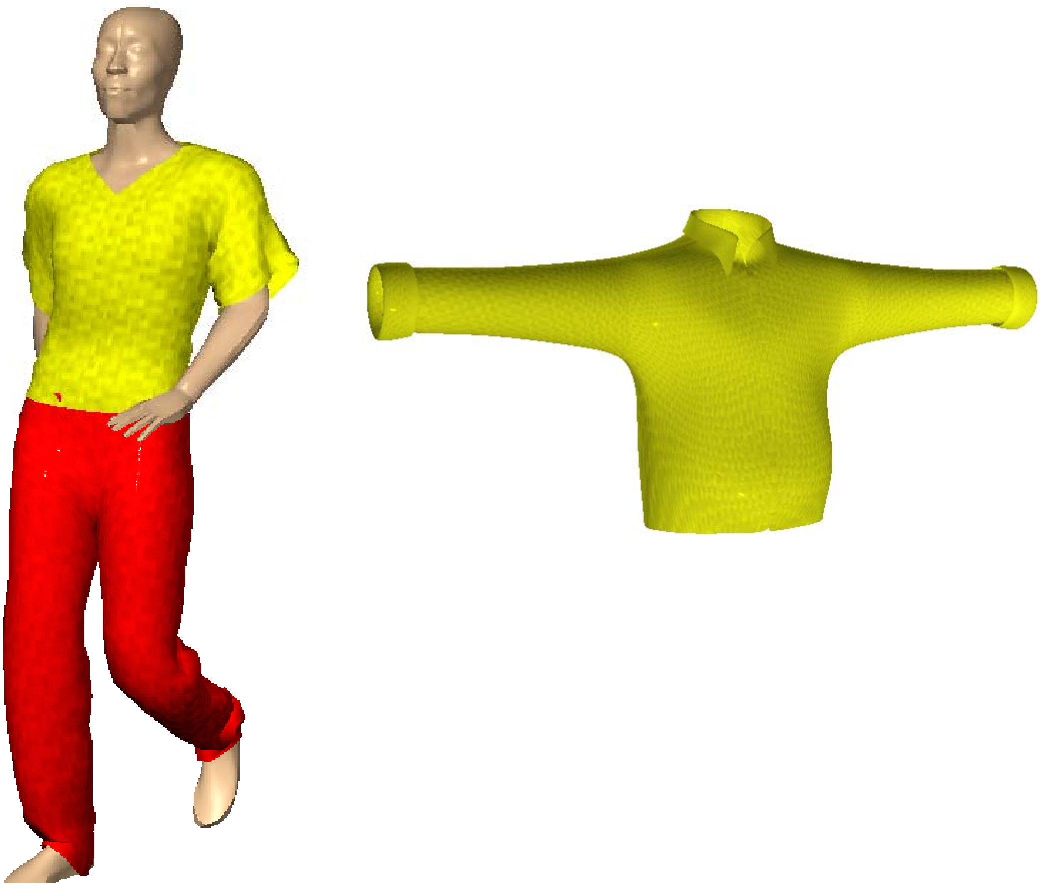

Figure 9. Walking man and shirt obtained from the BRDF model and virtual cloth structures

VI. Conclusion

Computation of a reflectance model forms the heart of every rendering method, because it provides the illumination of object in the scene, and therefore the colour of pixels in the image. Numerous empirical and theoretical models for the local reflection of light from surface have the same goal of reproducing real reflectance function, but the respective approaches are very different. Moreover, these models are rarely adapted for textiles, which are very anisotropic materials. So, we proposed the first results of our work in order to obtain a reflectance model physically plausible for textile. This is accomplished with a model that is physically linked to the material's surface properties. Nevertheless, to access these properties, several methods have been developed such as a virtual surface profiler for yarn. The results are quite promising, which is a reason to extend this work to other textile materials, especially to woven and knitted fabrics.

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